Jet Measurements in Pb+Pb Collisions from the LHC

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2nd Workshop on Jet Modification in the RHIC and LHC Era
Wayne State University, Detroit, MI, USA
Tuesday August 20, 2013

Preliminaries

- Presenting results from ALICE, CMS and ATLAS (AA)
  - Best attempt to collect up-to-date public results
- Cover subset of jet quenching observables measured with reconstructed jets
  - Heavy flavor jets and EW observables not covered here
    - See dedicated talks on these subjects
- Experimentally, HI jet observables entering era of precision measurements
  - We’ve got our hands full with baseline measurements and reducing systematics
  - ➡ Important to stop and consider implications of what we already know and incorporate it into future plans

Jets in Heavy Ion Collisions : Experimental Issues

- Jets have been used extensively in high energy community as analysis objects and many issues have been worked through:
  - Theoretical foundations, IRC safety
  - Calibration techniques/detector response/noise
  - Corrections for experimental effects
- Where possible, try not to reinvent the wheel
  - Learn from Snowmass!
  - Following in HEP footsteps also natural for LHC experiments
- HEP community trying to deal with high pileup of future LHC conditions
  - Natural time for synergy for experimental techniques between two communities
  - However techniques developed for pileup environment may not be the best for HI

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Jets in Heavy Ion Collisions : Experimental Issues

- **Main HI problem: how to (experimentally) separate jet signal from UE**
  - **We (currently) know too little about jet vs medium response to apply a completely satisfactory solution to this problem *a priori***
  - **In early measurements, apply careful experimental operating definition (e.g. ATLAS):**
    - **Energy clustered in a jet reconstruction algorithm above the uncorrelated UE**
    - **May include medium response (correlated)**
- **All experiments attempt to subtract an unbiased estimate of the uncorrelated UE using area-based method**
  - ➡ **Details outside the scope of this talk**
- **Must apply correct procedure (e.g. unfolding) to account for residual experimental effects**

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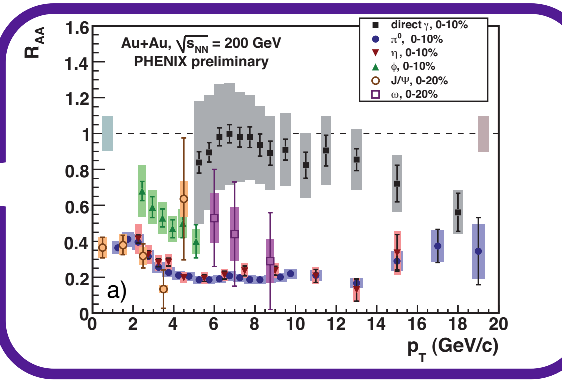
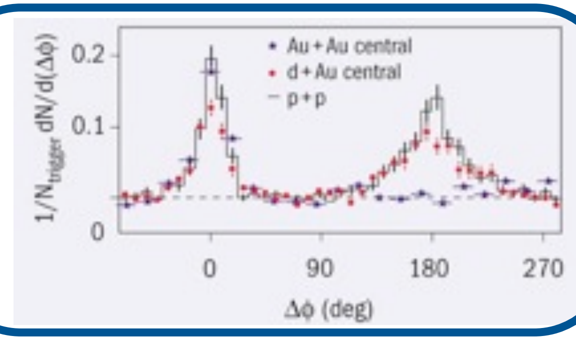
What We Know from RHIC

- **Indirect observation of quenching established by two key measurements**
  - **Suppression in rate of inclusive hadron production at high p_T — nuclear modification factor R_{AA}**



  - **Modification of di-hadron azimuthal correlations**

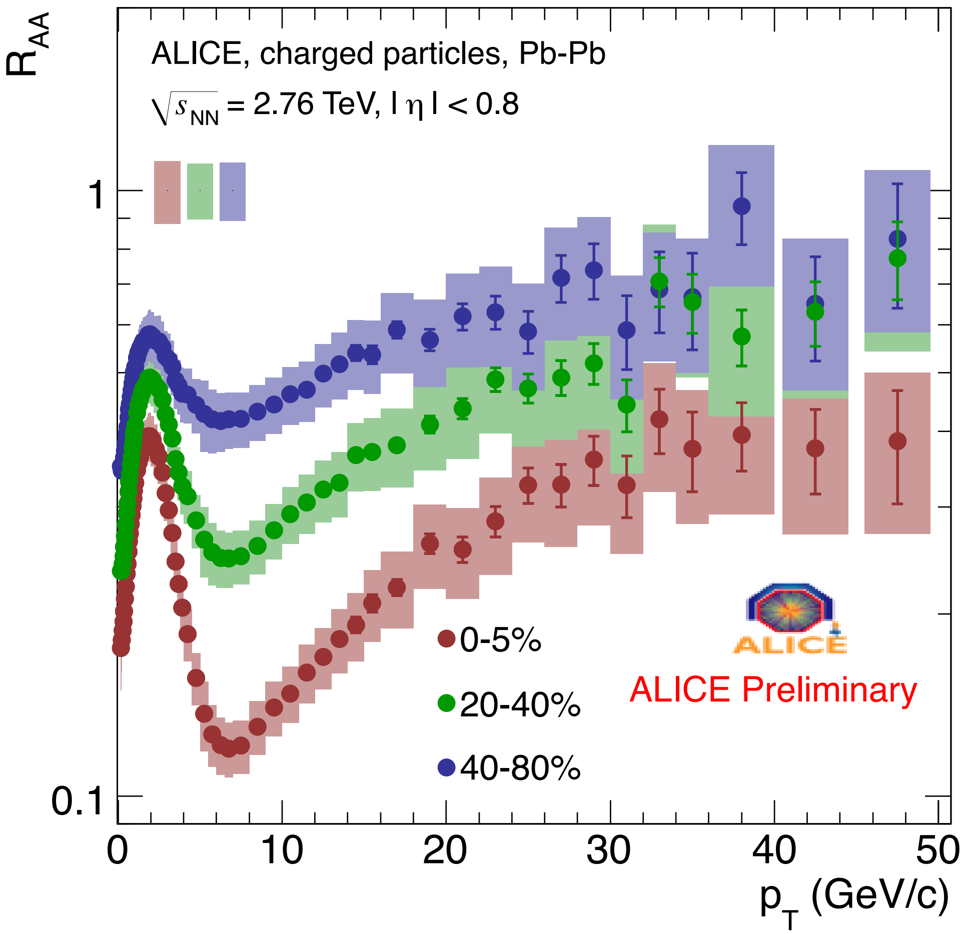


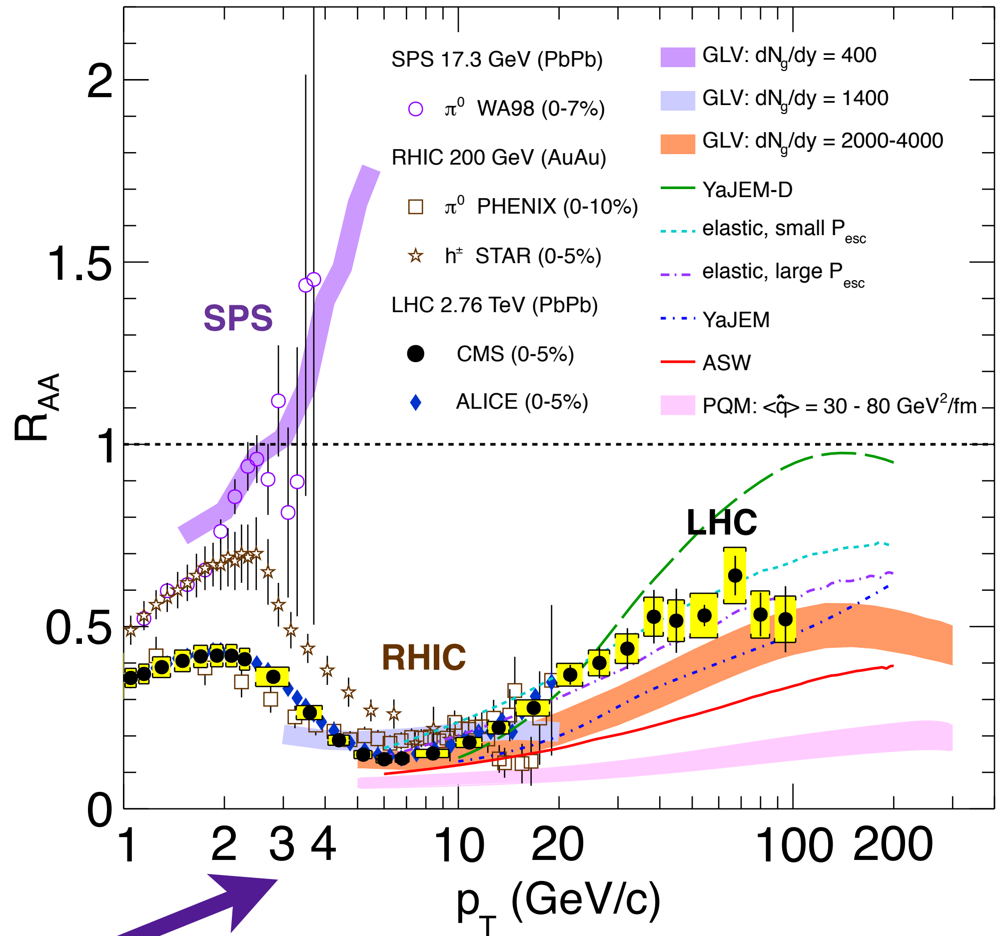
➡ **QCD factorization is explicitly broken in nucleus—nucleus collisions**

- ***"Phase 0" of an LHC jet quenching program is to extend these exact measurements to the LHC***

- ***"Phase I" is to perform analogous measurements with fully reconstructed jets with high precision***

Phase I: Extending the Familiar to the LHC





- **Add LHC measurements to the picture**
- **Gradual rise in R_{AA} manifest feature of suppression**

ATLAS EXPERIMENT

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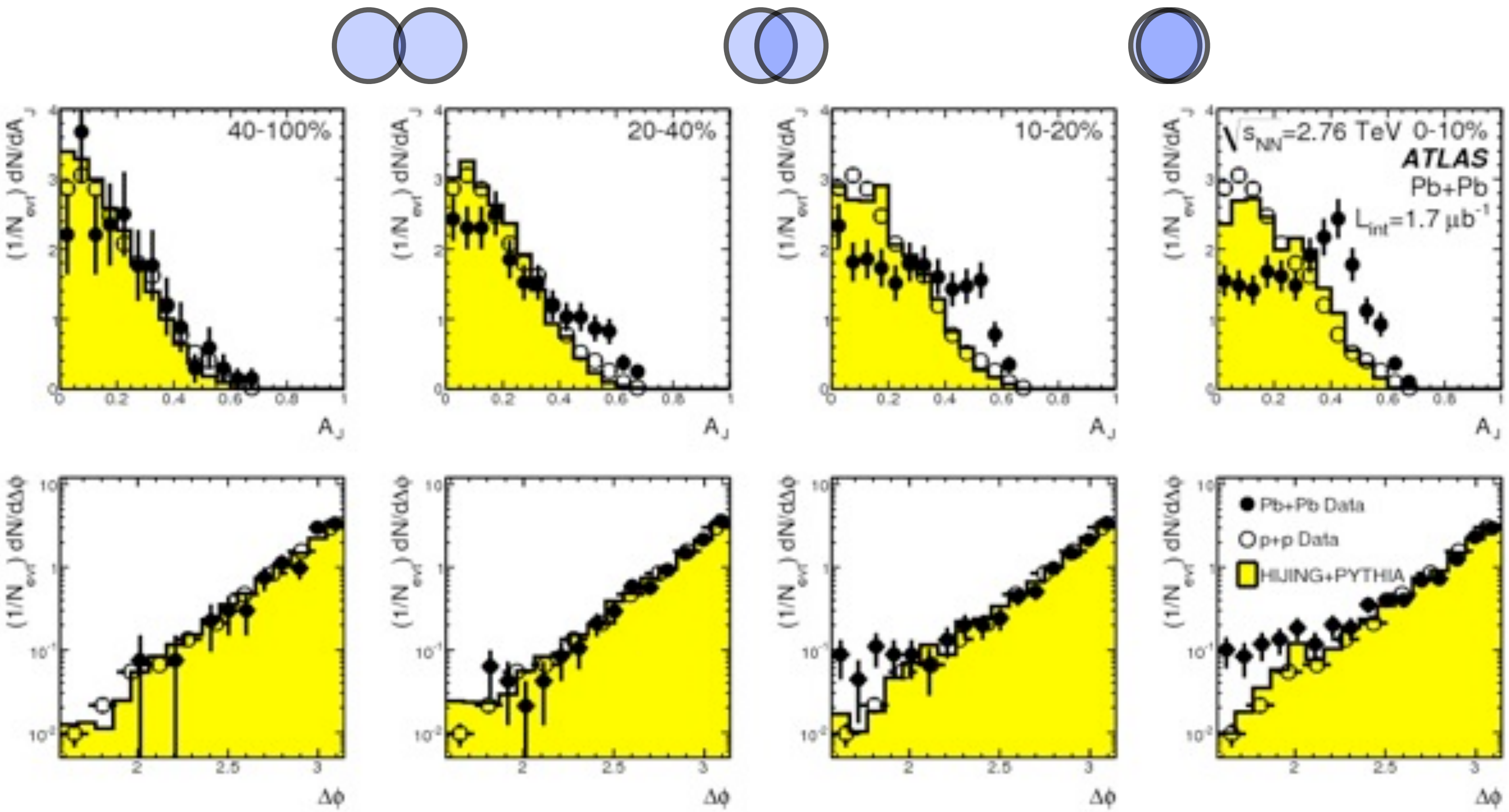
Ushering in the LHC Era: Dijet Asymmetry



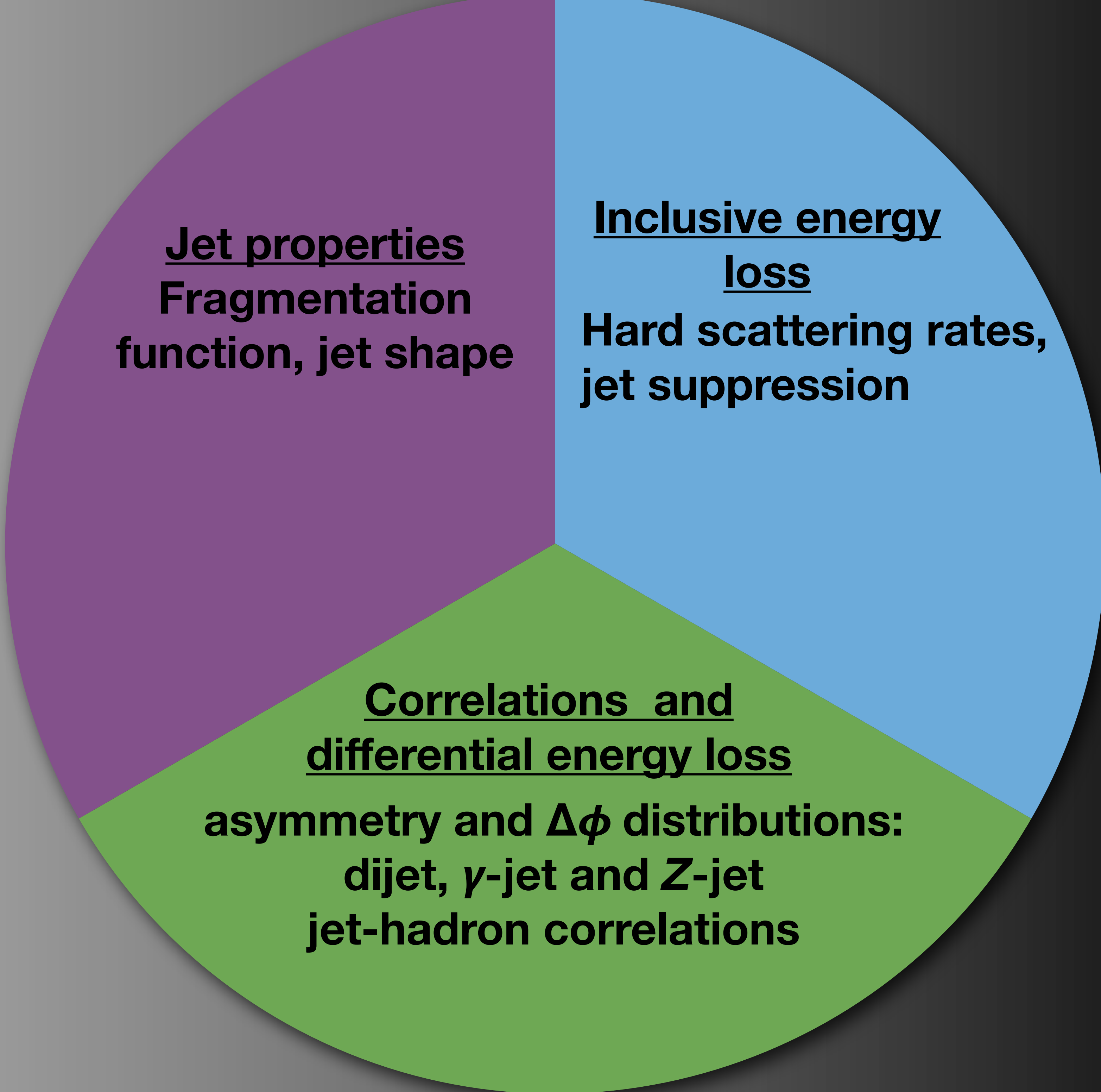
$$A_J = \frac{E_T^1 - E_T^2}{E_T^1 + E_T^2}$$

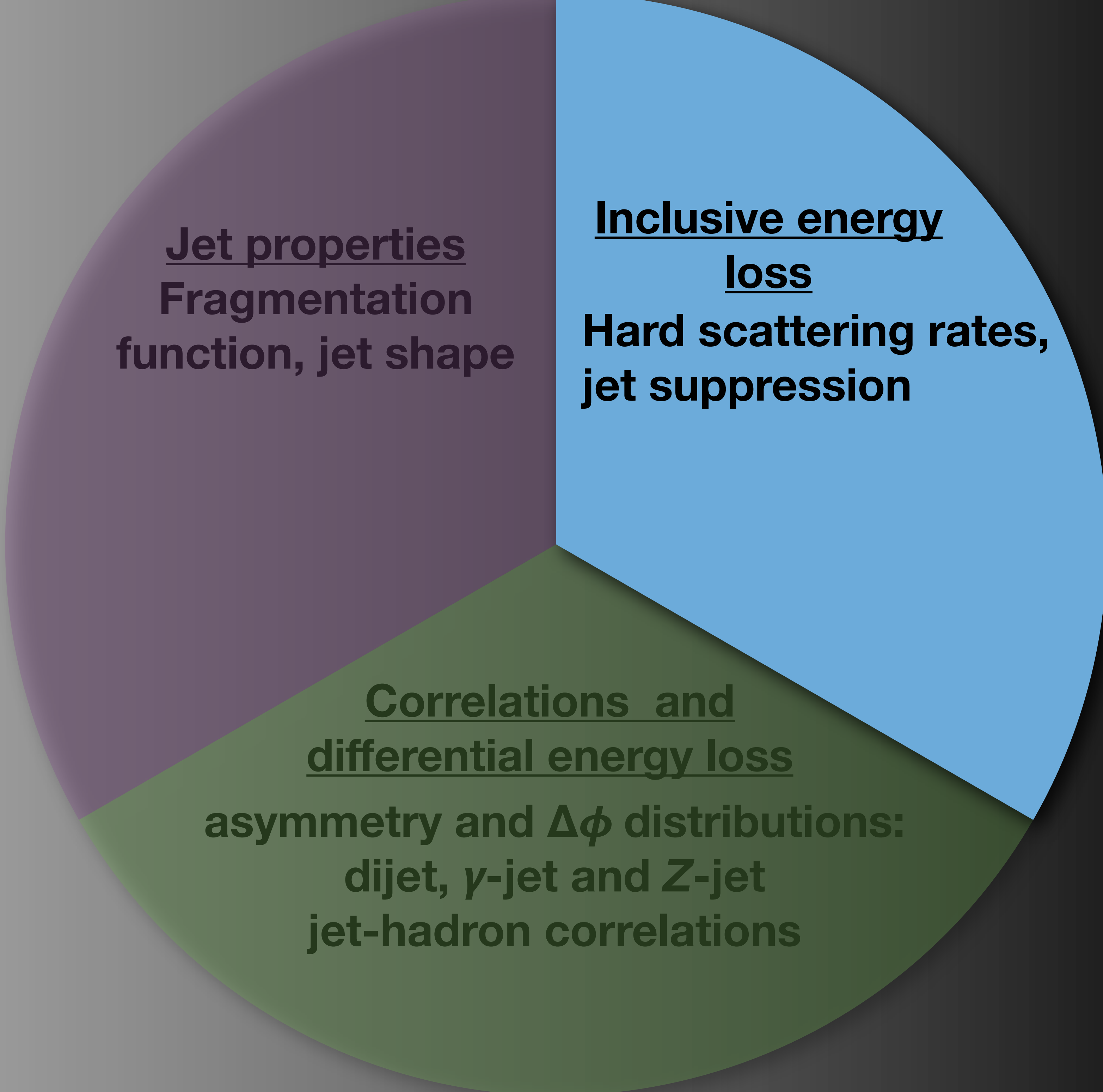
$$E_{T1} > 100\ GeV$$

$$E_{T2} > 25\ GeV$$

First direct observation of jet quenching

Significant fraction of events with enhanced dijet asymmetry while simultaneously preserving the back-to-back angular correlation


Jet properties
Fragmentation function, jet shape
Inclusive energy loss
Hard scattering rates, jet suppression
Correlations and differential energy loss
asymmetry and Δϕ distributions:
dijet, γ-jet and Z-jet
jet-hadron correlations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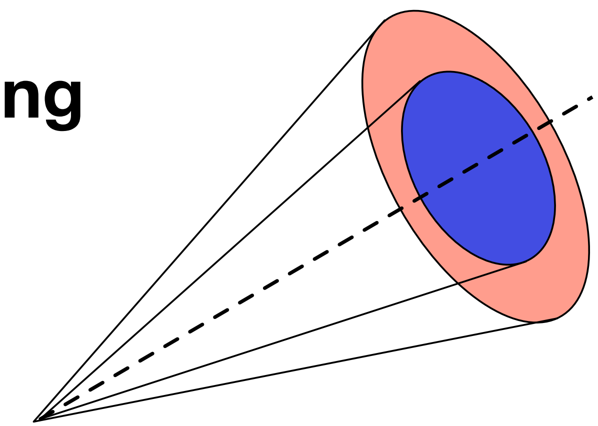
Inclusive Jet Suppression

- What about centrality-dependent modification of jet spectra?
  - Jet kinematics more sensitive to parton suffering energy loss
  - Access dynamics of full parton shower

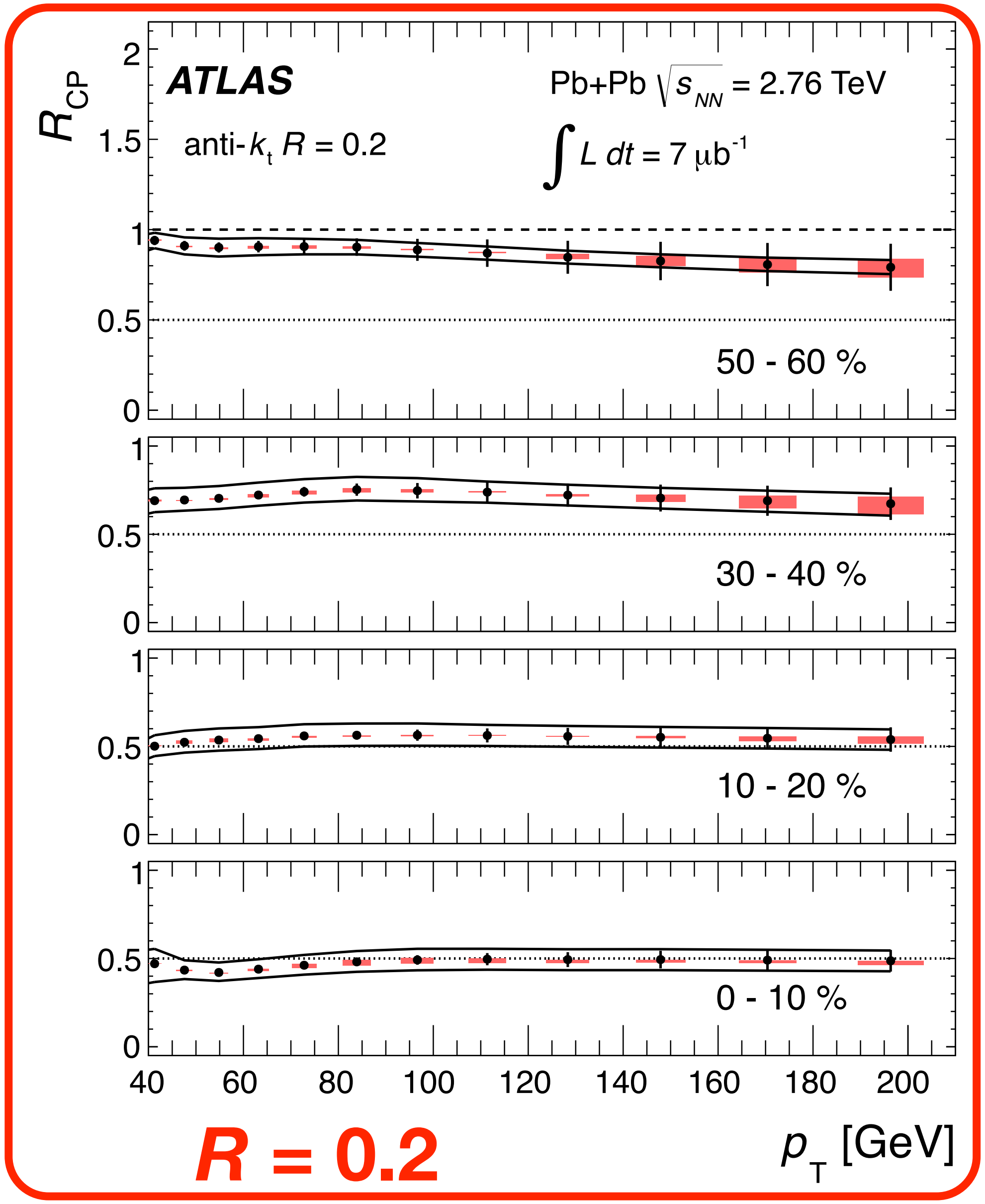
- Medium effects may cause jet energy to be transported outside the nominal jet cone

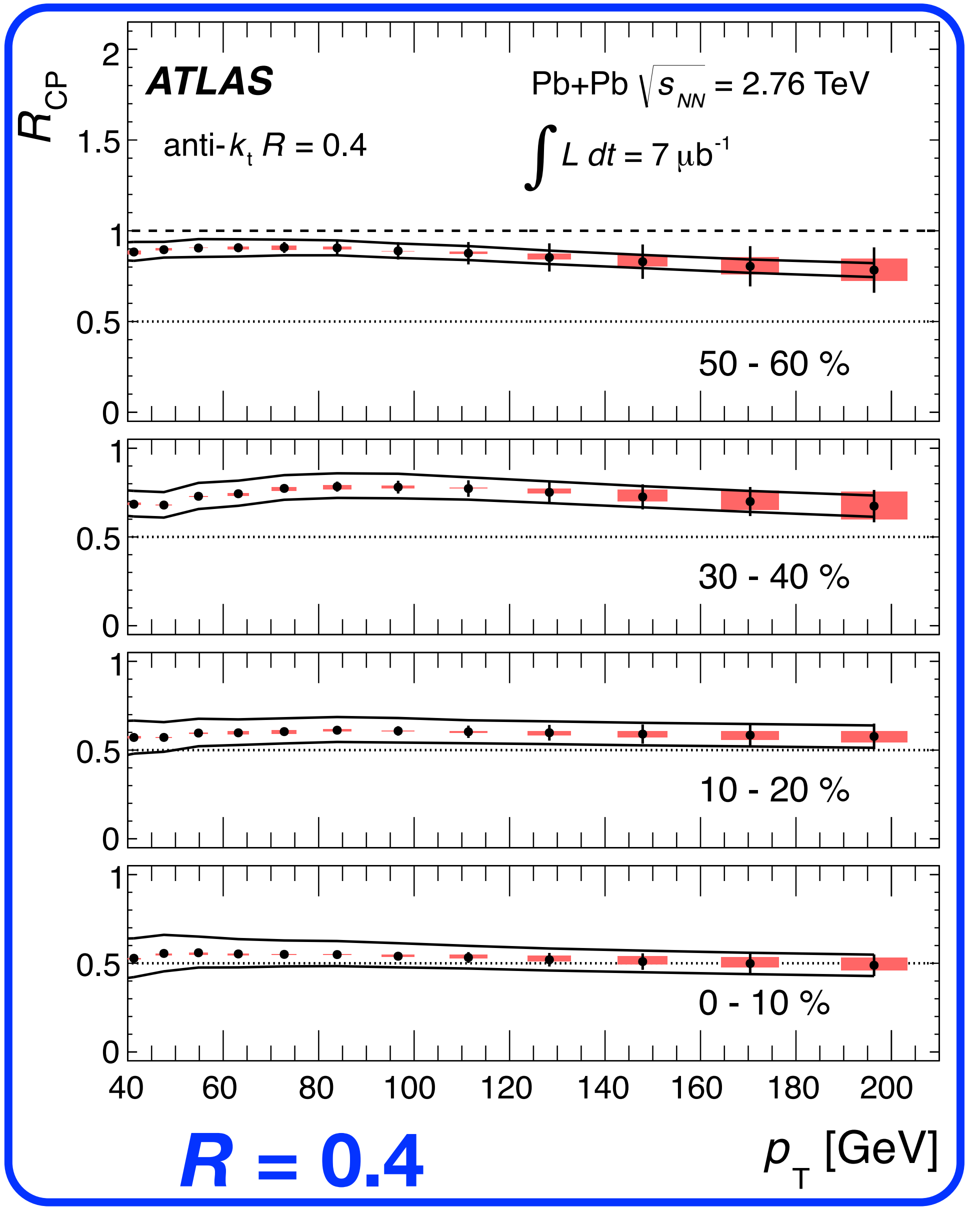
- Can lost energy be recovered by expanding size of jet definition (radius) ?



➡ **Measure single jet suppression with multiple jet sizes**

Results: R_{CP} vs p_T in Centrality Bins





Use 60—80 % as peripheral reference

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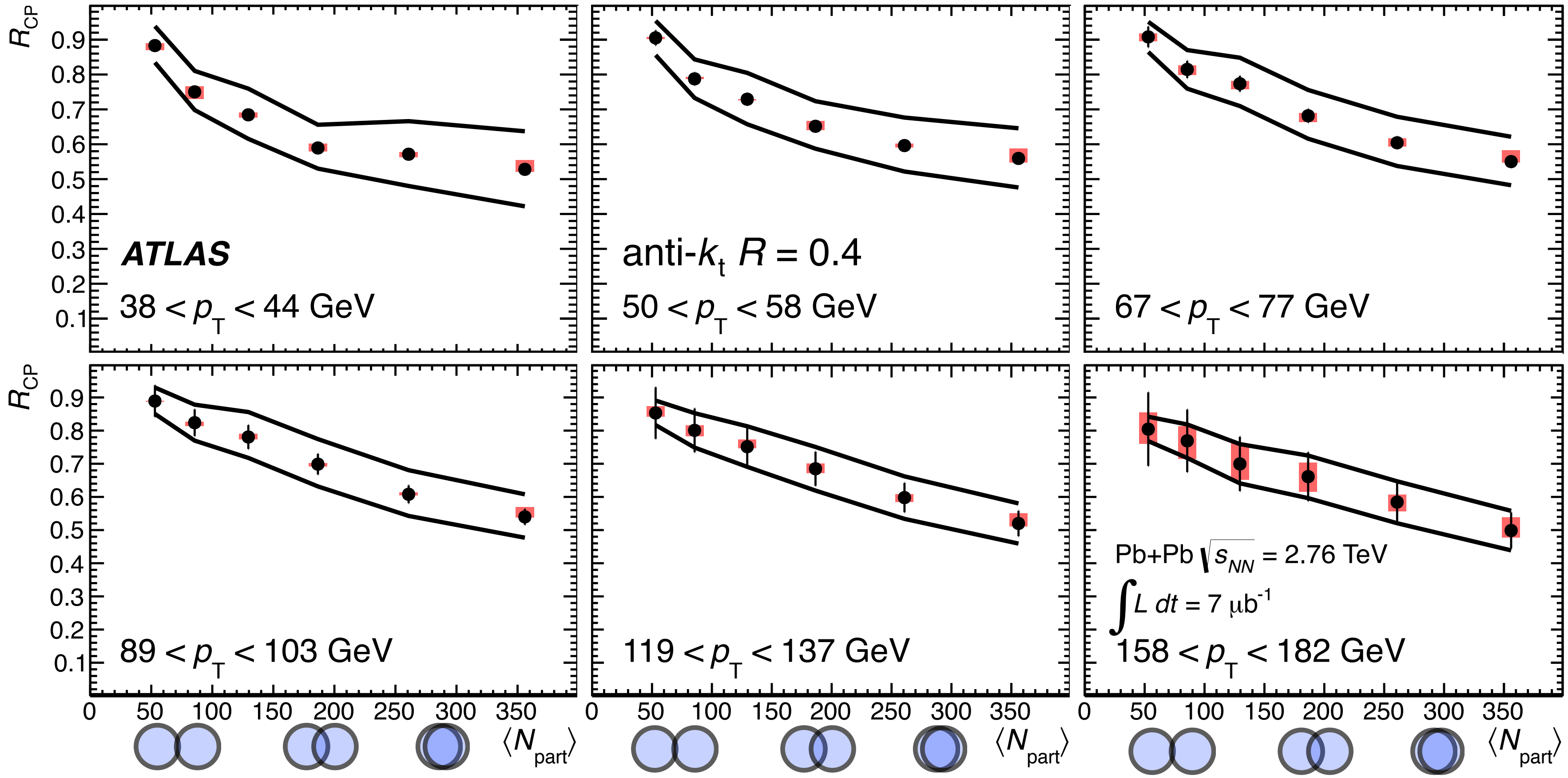
Results: R_{CP} vs N_{part} in p_T bins



- **Centrality dependence as represented by N_{part}**
- **Suppression turns on differently for high and low p_T jets**

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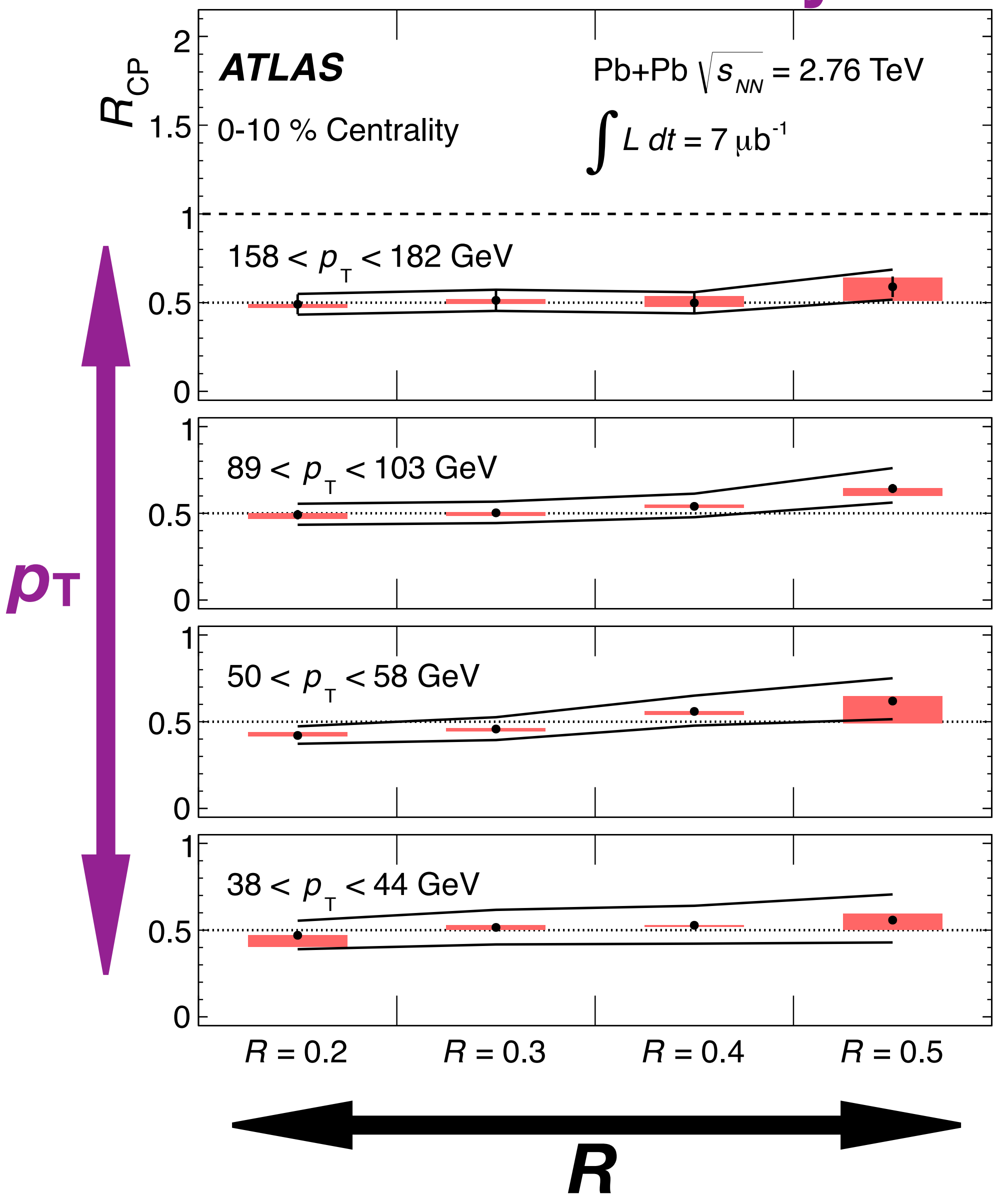
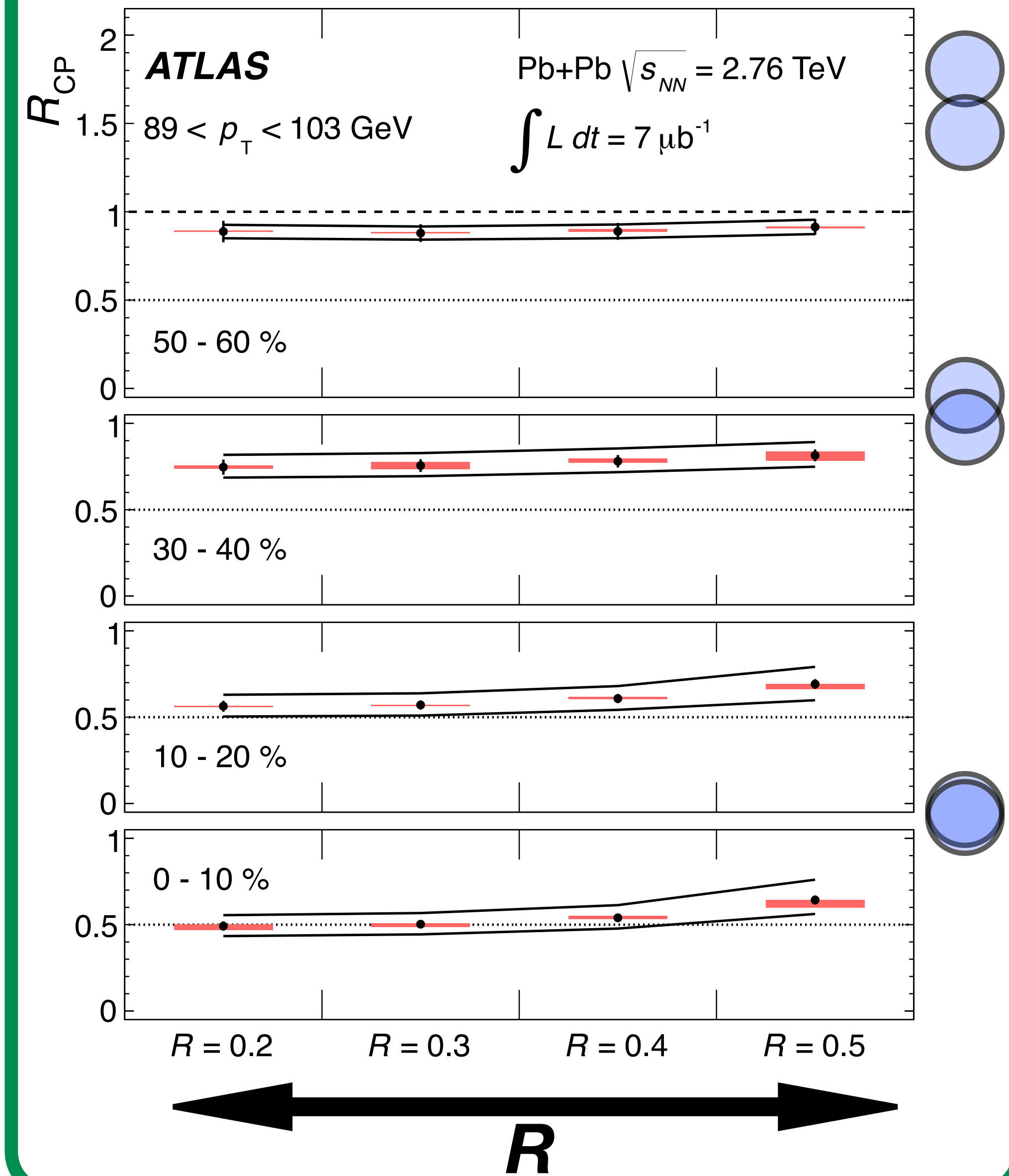
Results: R_{CP} vs R

0—10% centrality



89 < p_T <103 GeV



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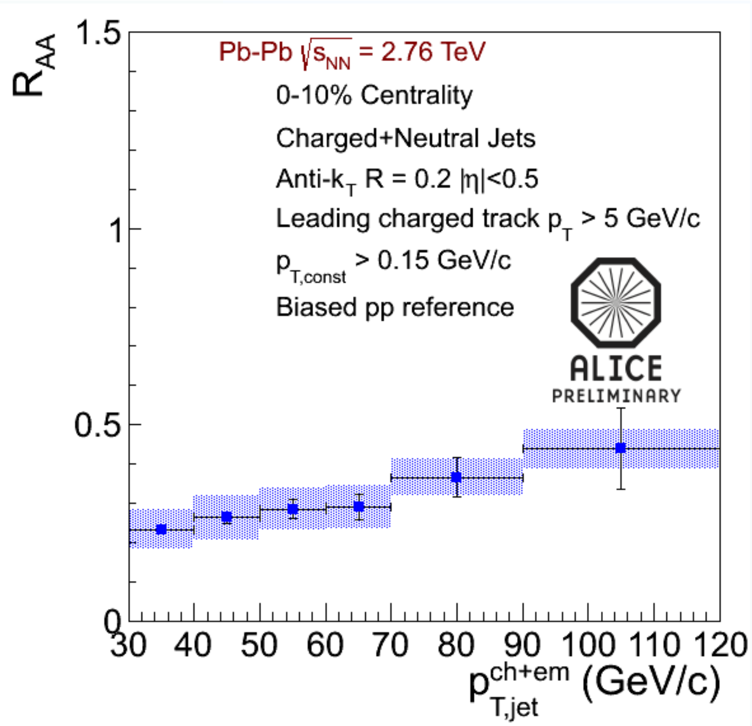
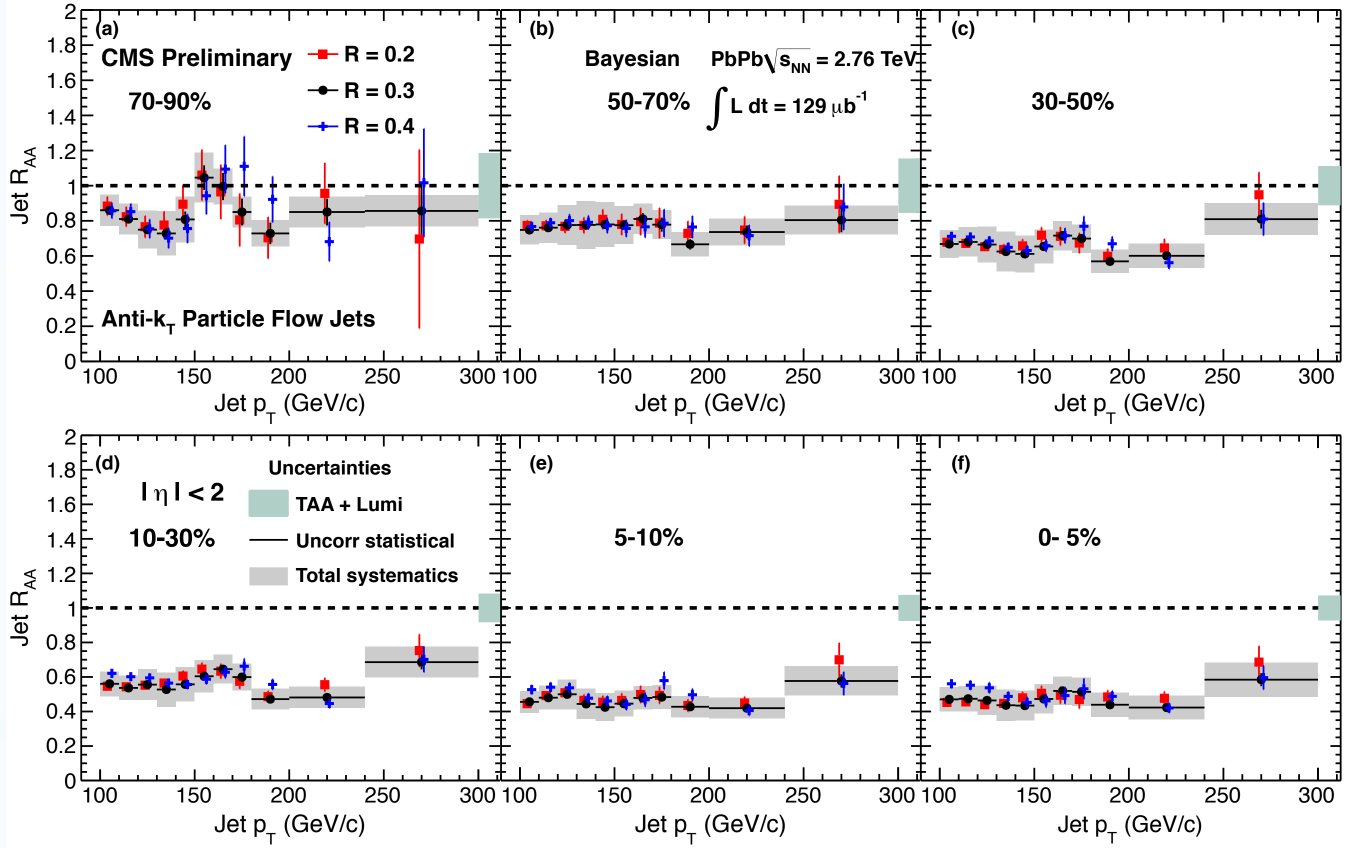
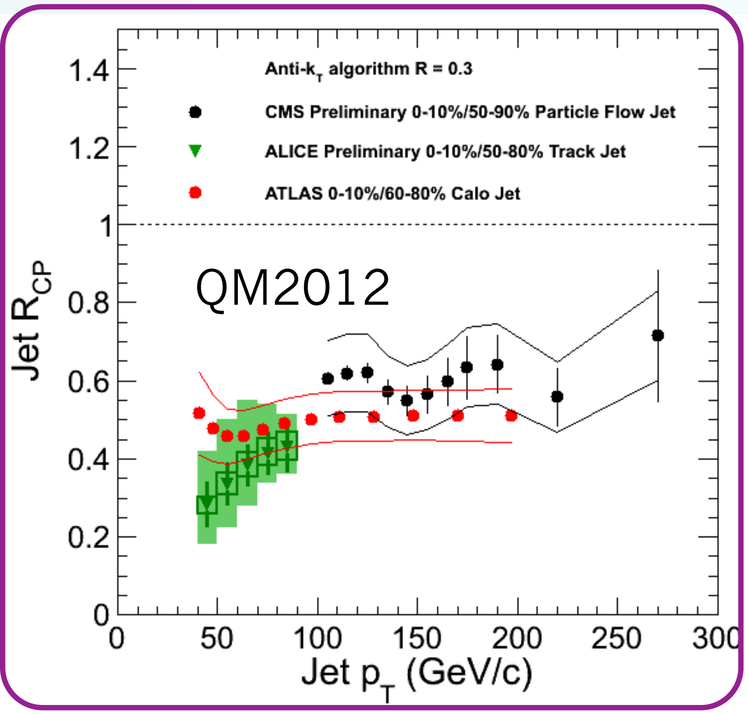
R_{AA}







- As of ~ 1 year ago (QM2012), all experiments seeing comparable degree of suppression and similar trends with p_T, centrality and R

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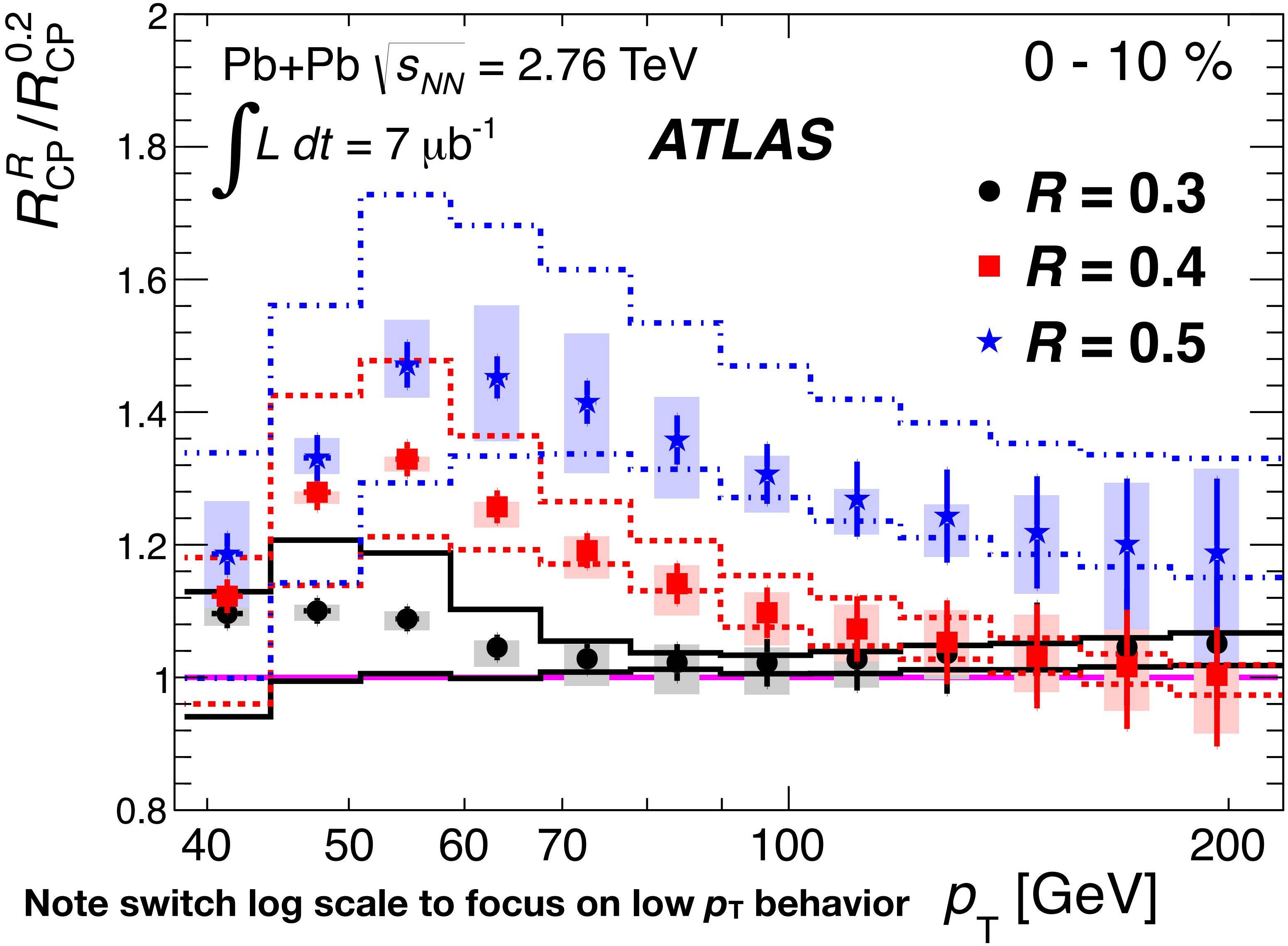
Quantitative statement of *R* dependence



Ratios of R_{CP} to R_{CP} with *R*=0.2

Measure *relative* suppression with respect to most suppressed *R* value (*R*=0.2)

Variation with R is significant

Note switch log scale to focus on low p_T behavior

- **Many systematics cancel, correlated between different *R***
- **Statistical correlation between different *R* values included and propagated through unfolding**

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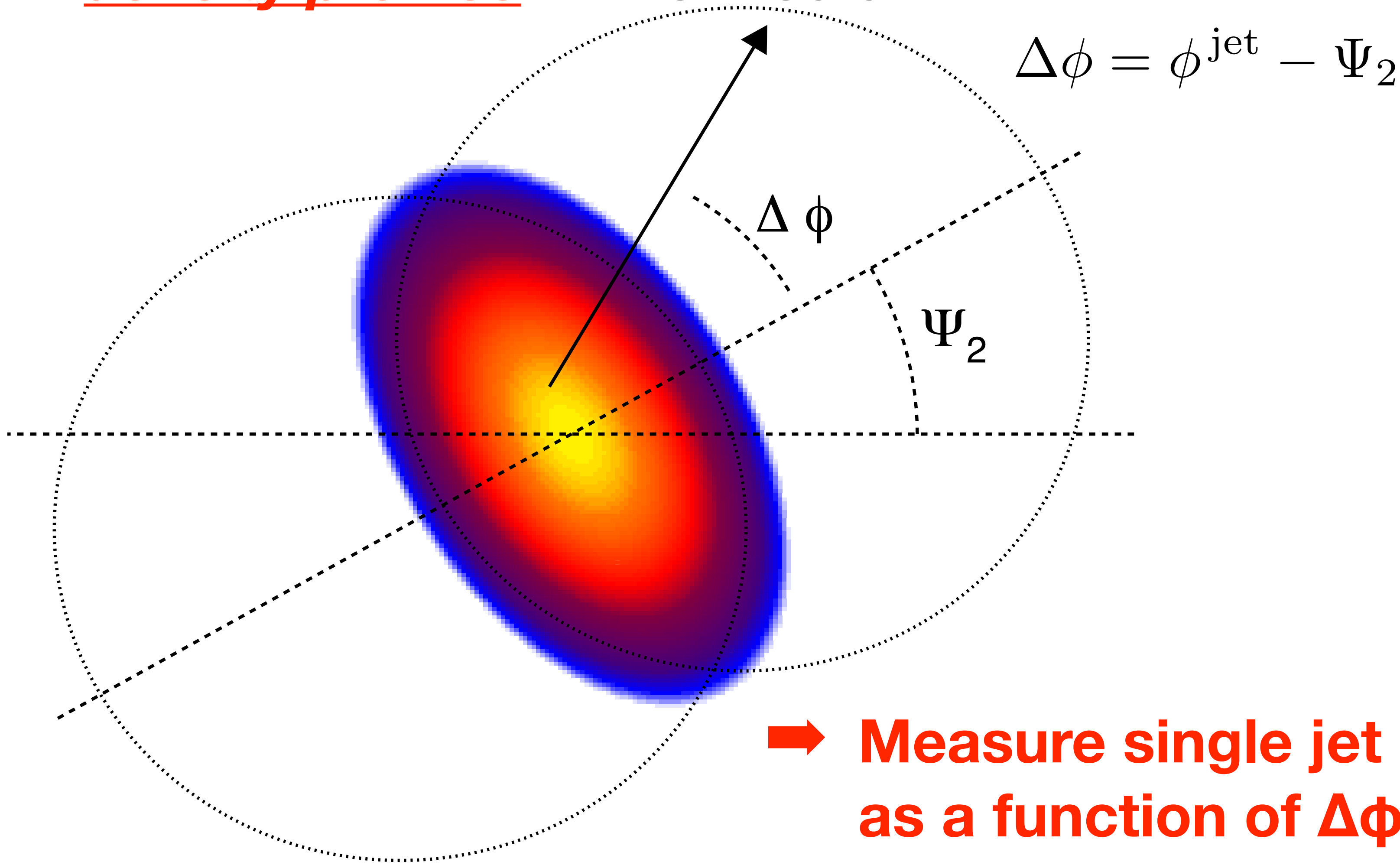
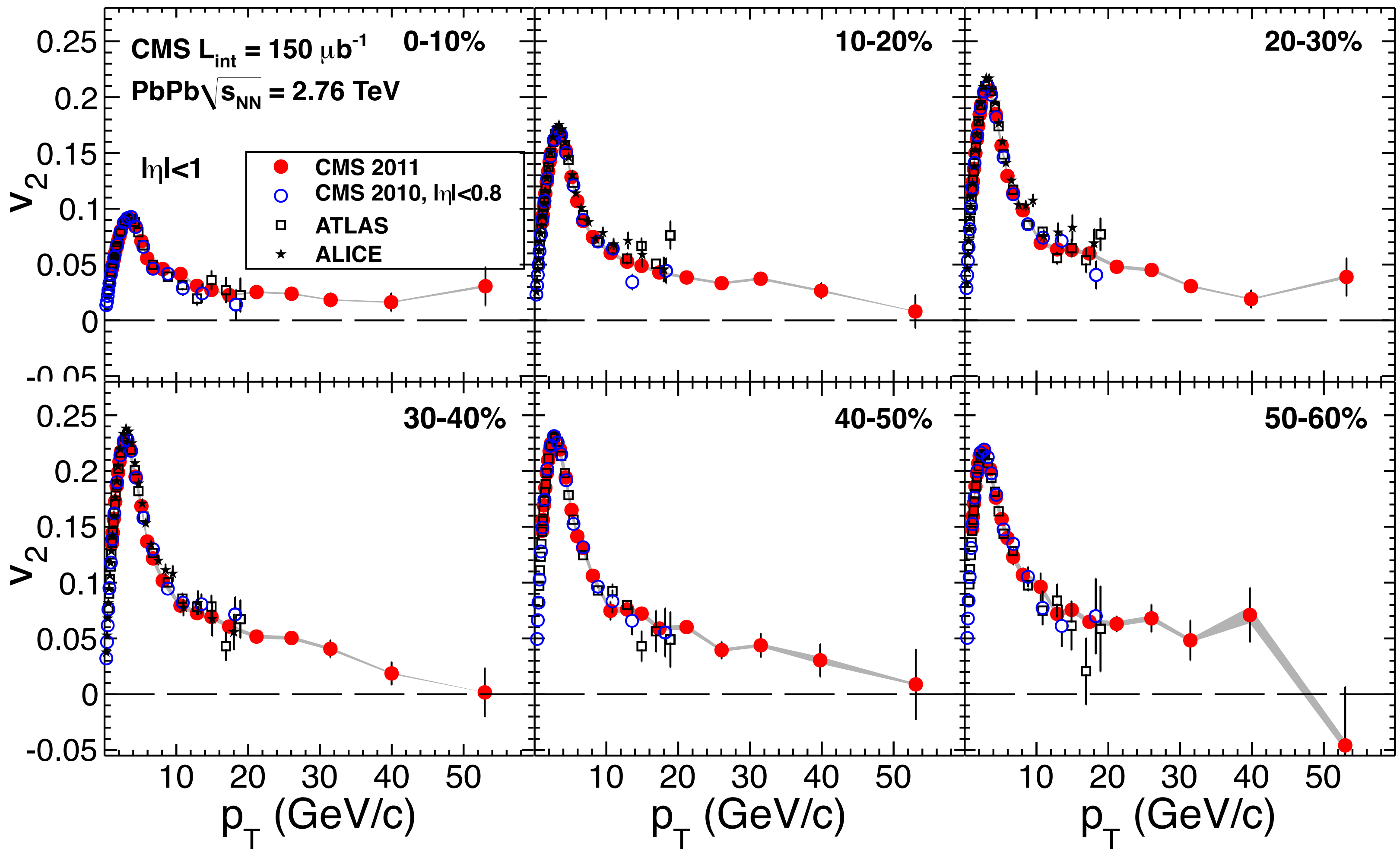
Jet Suppression and Collision Geometry

- **Jets produced with different angles with respect to event plane (Δφ) will see *different path lengths and density profiles* in the medium**



➡ **Measure single jet suppression as a function of Δφ : $v_2^{\rm jet}$**

Jet Suppression and Collision Geometry



- **Significant non-zero modulation of hadron yields at high p_T**
- **Weak p_T dependence: jets dominating production of hadrons p_T 20-50 GeV have similar v_2 values**
- **Leads to similar expectation for jets**

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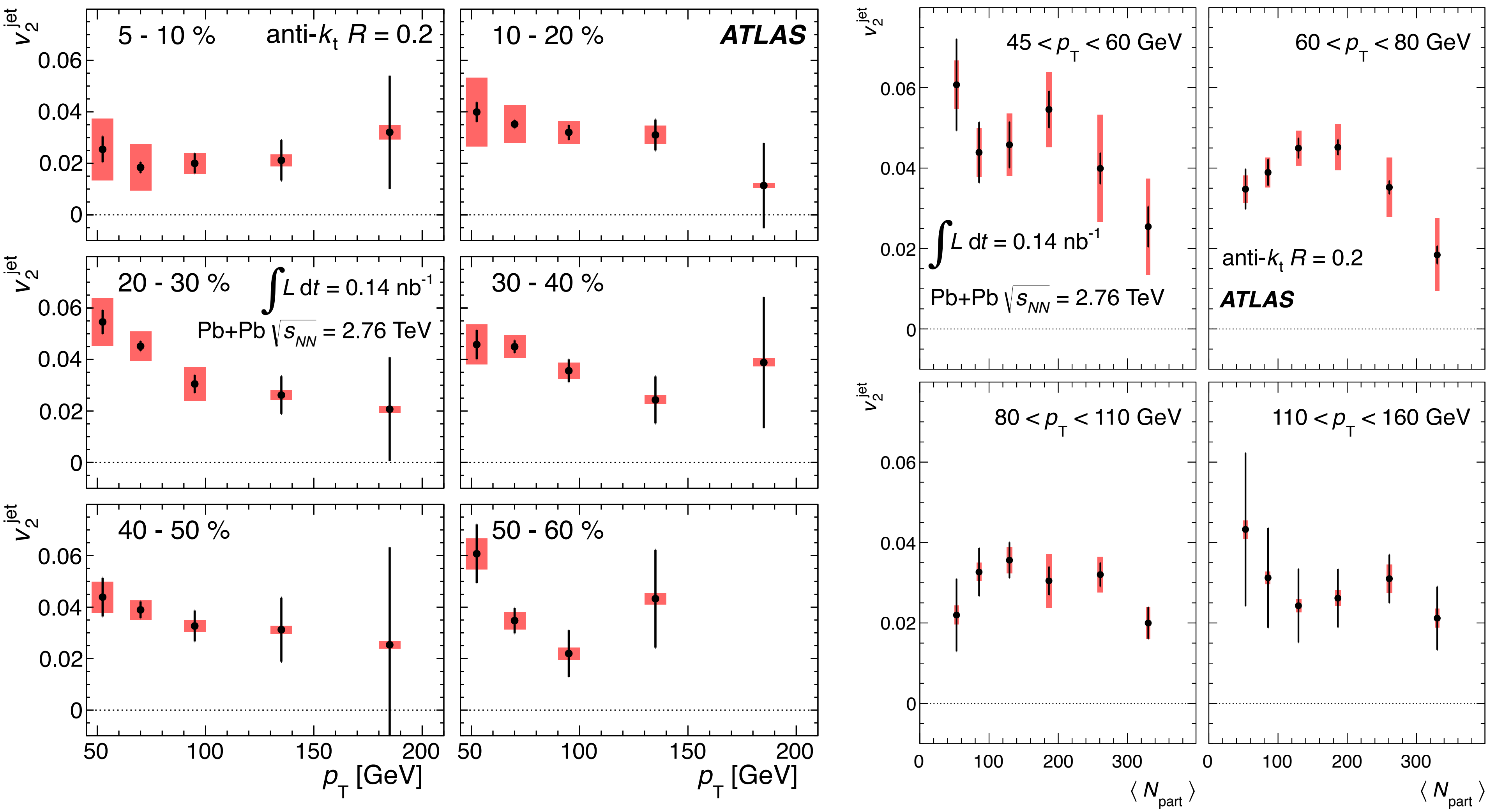
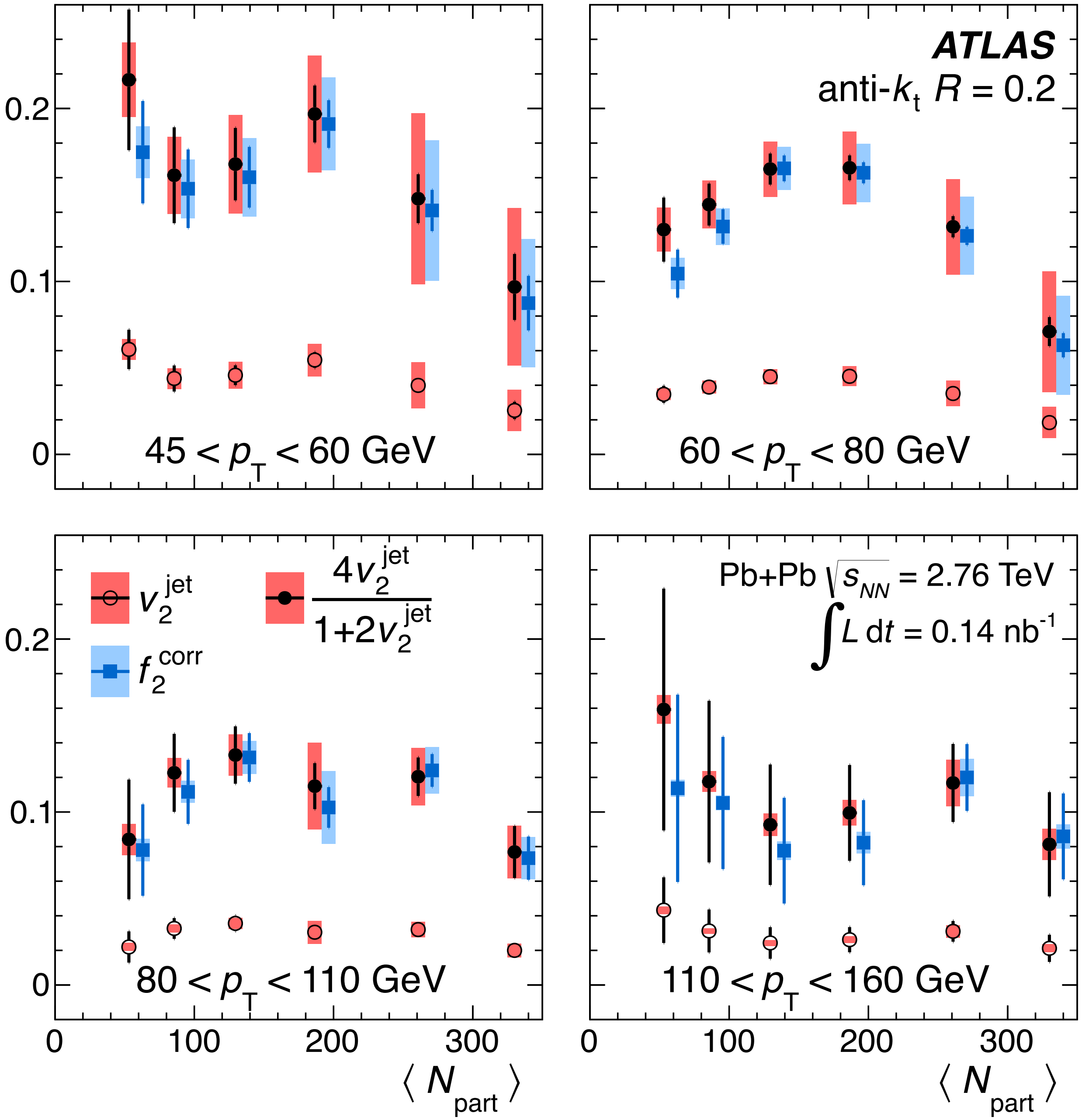
Jet Suppression and Collision Geometry



- **1-5% modulation of yield**
- **Centrality dependence consistent with naive expectation from geometric considerations**

Jet Suppression and Collision Geometry



- Compare ratio of yields at Δϕ=0 and π/2 to expectation from pure second harmonic modulation
- Almost no room for different modulation modulation (e.g. $\cos^2 2\Delta\phi$) which may be expected from non-linear path length dependence
- Need calculation with full realistic geometry

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Jet properties

Fragmentation function, jet shape

Inclusive energy loss

Hard scattering rates, jet suppression

Correlations and differential energy loss

asymmetry and $\Delta\phi$ distributions:
dijet, γ-jet and Z-jet
jet-hadron correlations

Asymmetry: Differential Energy Loss

- γ/Z— jet correlations provide clean probe since γ and Z (or leptonic decay products) do not suffer energy loss

  ➡ Do NOT expect jets recoiling against γ/Z to have same p_T as γ/Z

  - Effects like initial state parton shower cause broadening of distribution
  - Focus on $x_J = p_T^{jet} / p_T^{\gamma/Z}$

- Unmodified x_J and A_J distributions in are different γ— and Z— jet events
  - Large virtuality required to produce Z
  - Potentially provide different handles on energy loss since intrinsic are different

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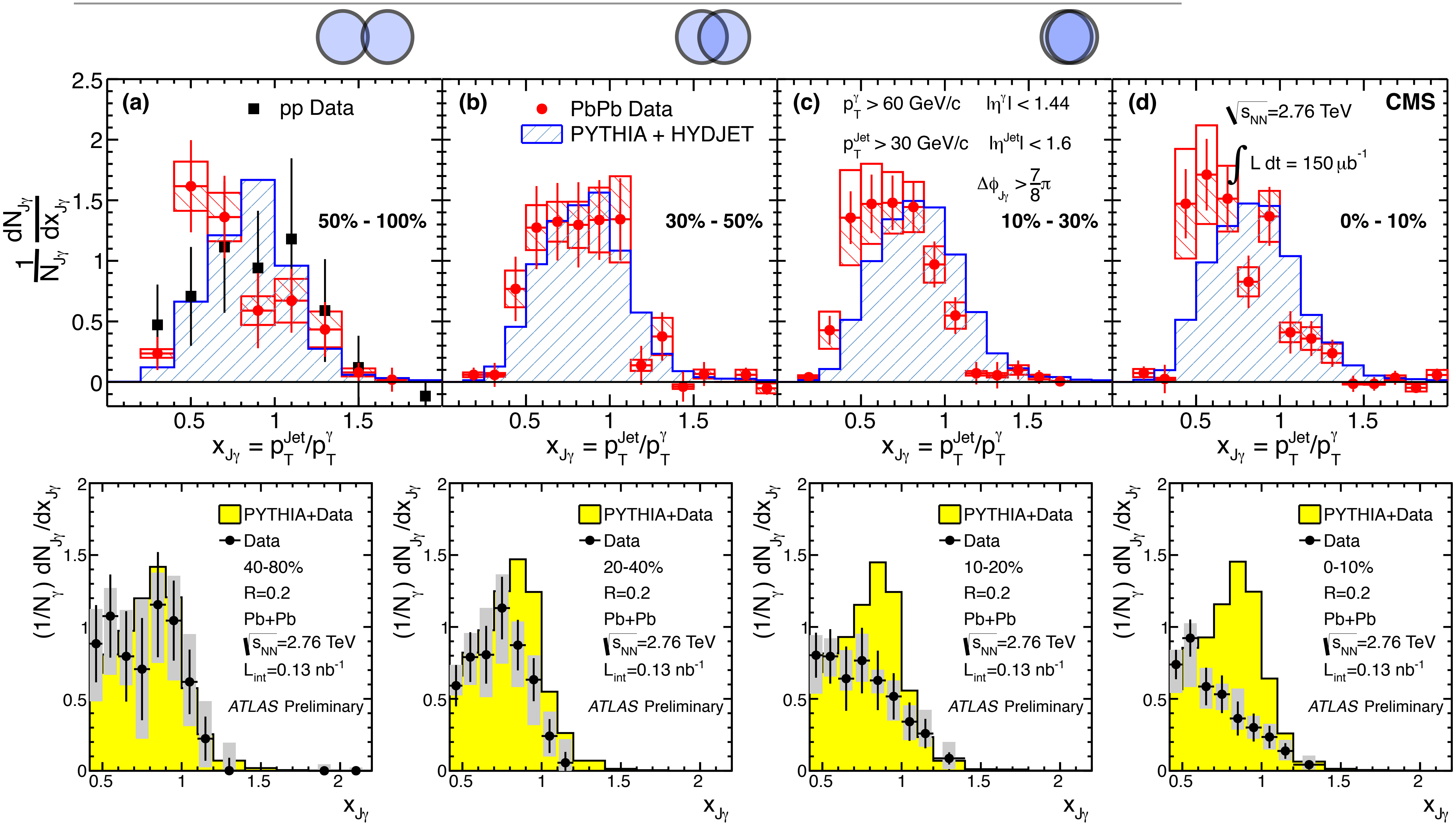
γ-jet: $x_{J\gamma}$ Distributions



- Slight differences in kinematic selection and analysis details but same general trend— large systematic shift to lower x values in central collisions

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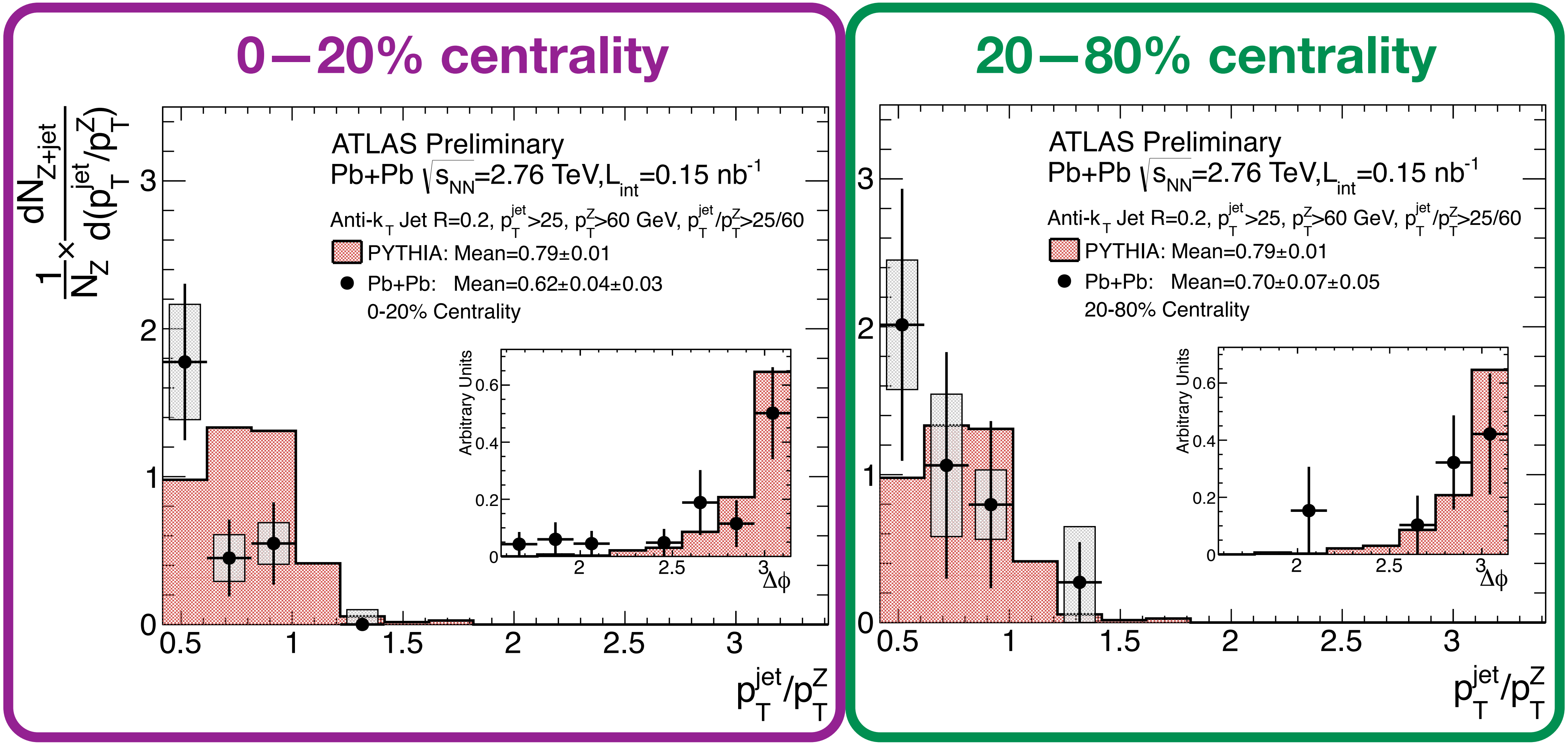
Z—jet Correlations



- **Mostly proof of principle due to low statistics but hints at potential of the measurement when more data comes**
- **General trend compatible with photon-jet results**

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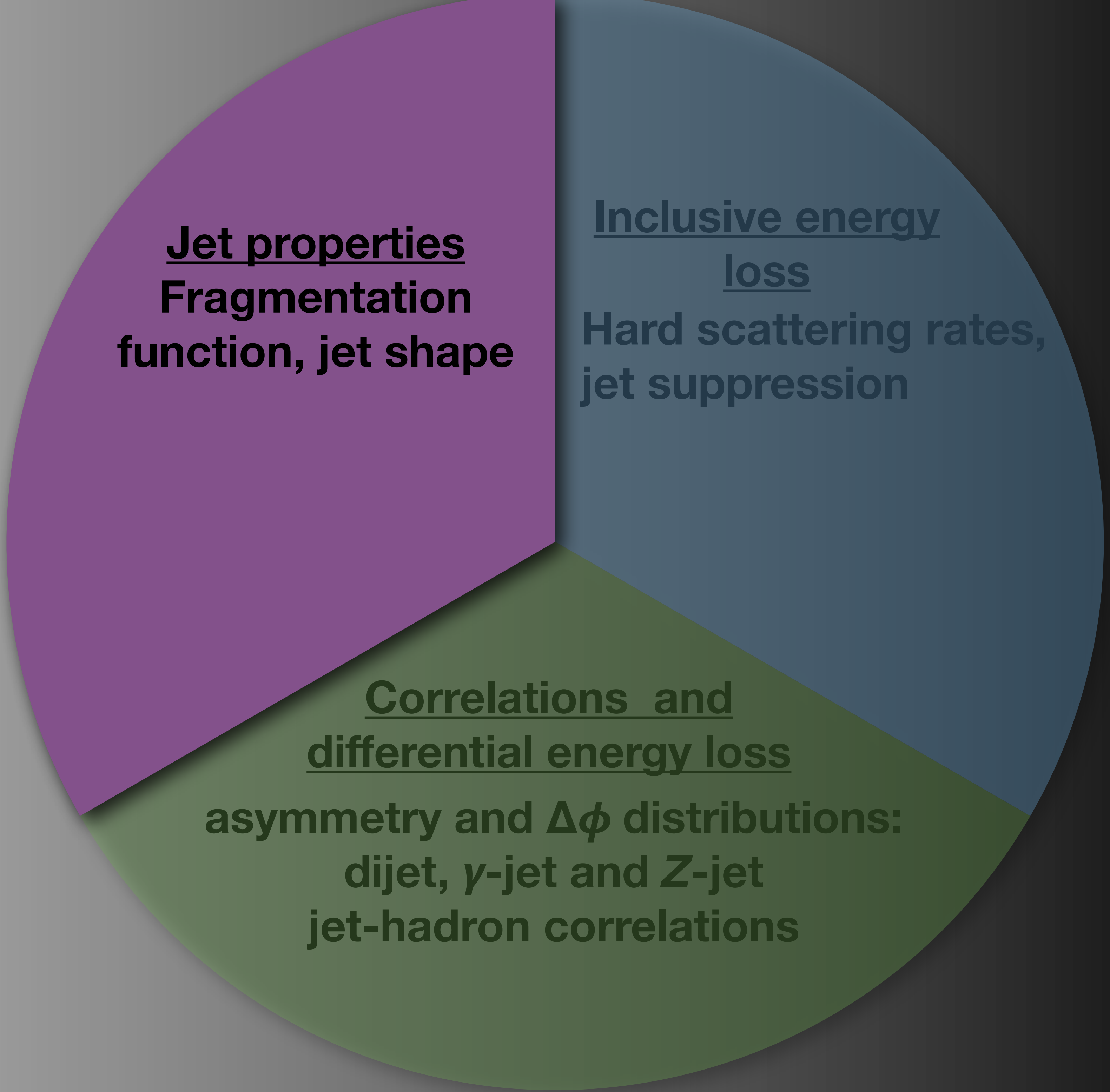
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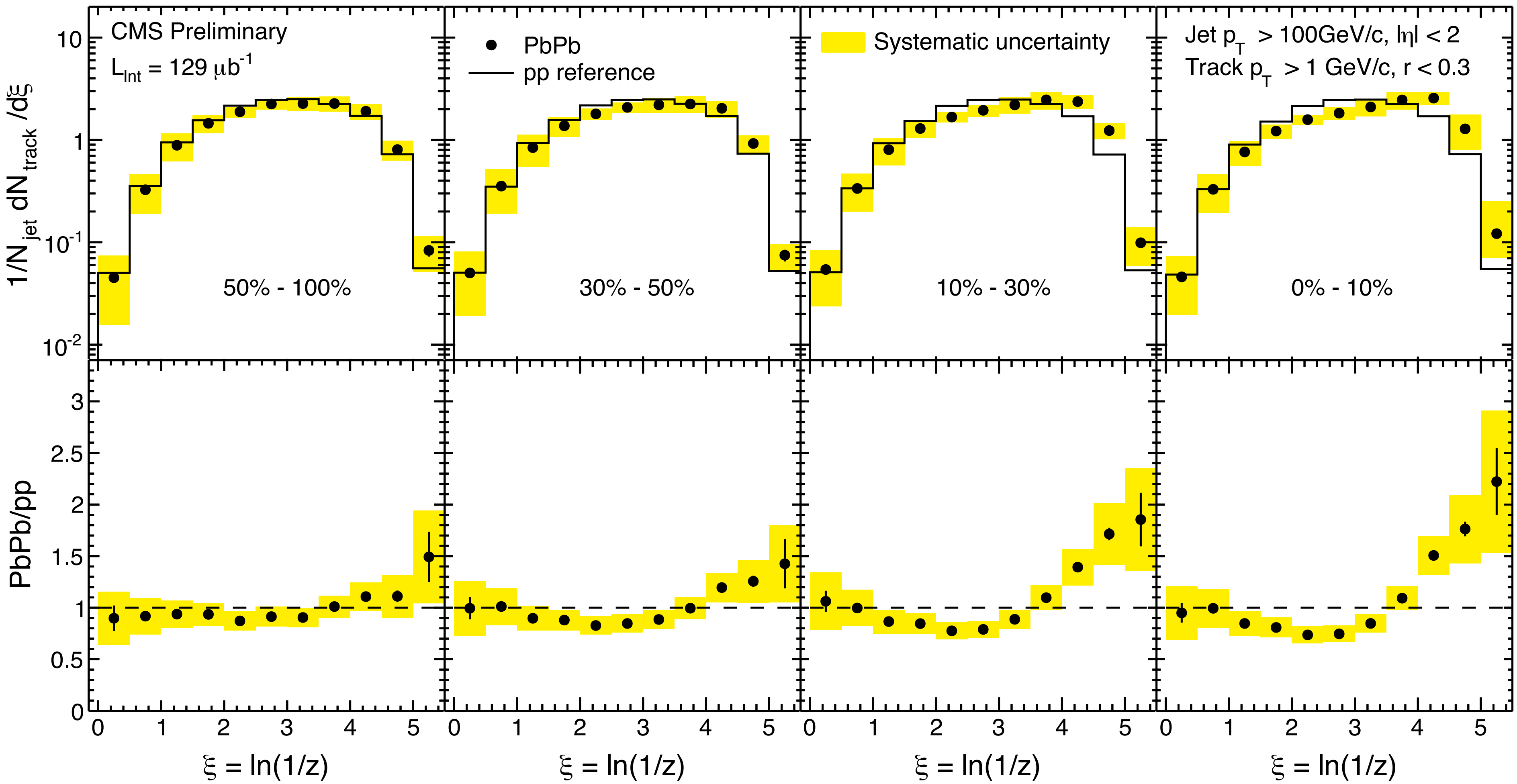
Jet Structure: Fragmentation Function



- Use tracks inside of jets
- Subtract UE contribution to correlation
- *z* is longitudinal momentum fraction

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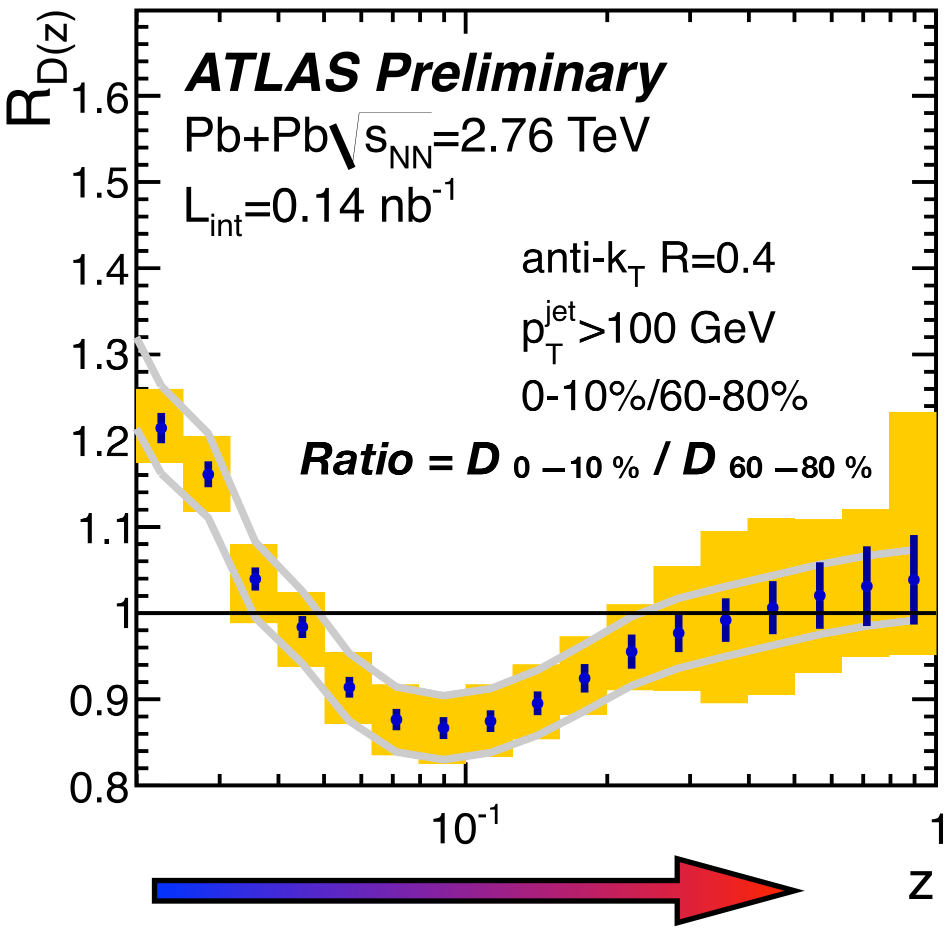
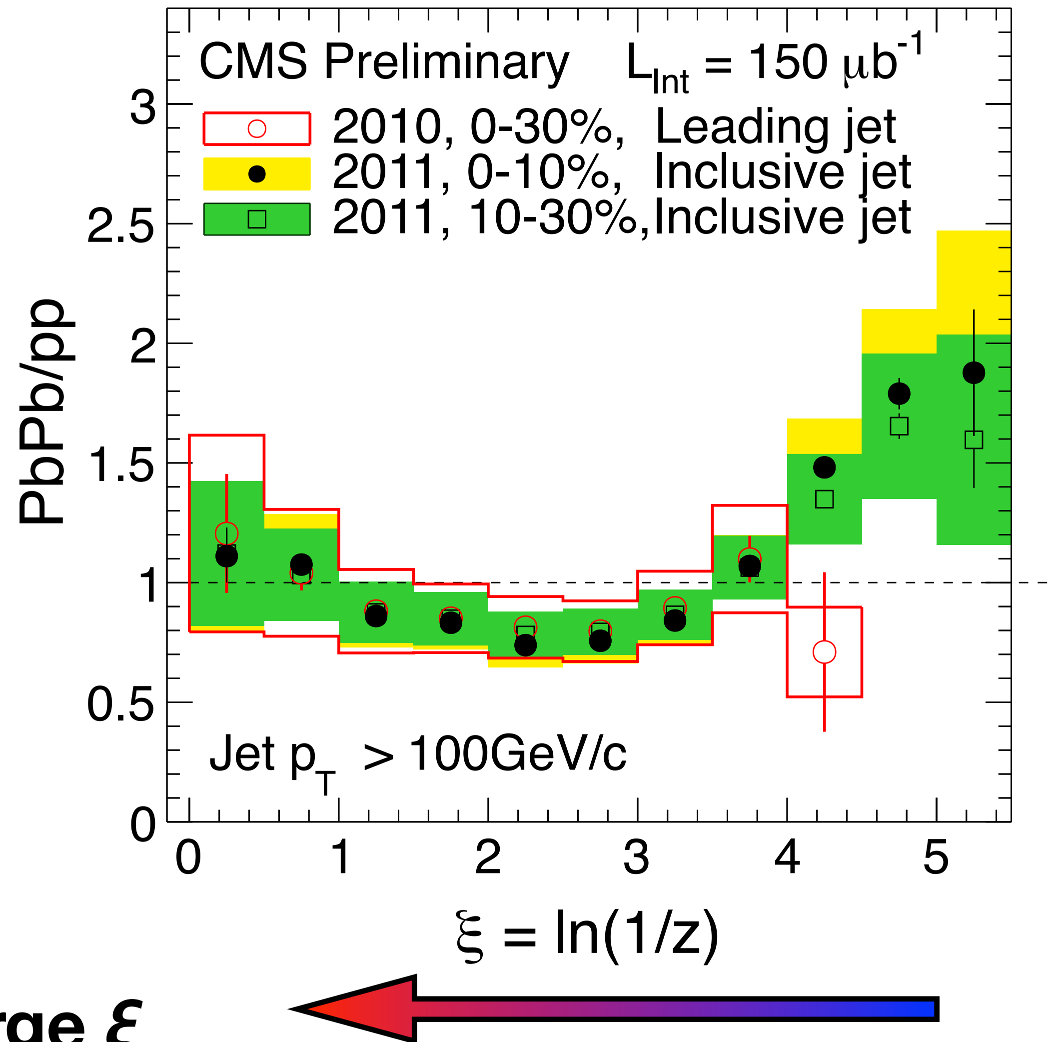
Jet Structure: Centrality Dependence





- **Enhancement at low *z*/large *ξ***
- **Suppression at moderate *z*/*ξ***
- **Hard component behavior may exhibit additional enhancement**

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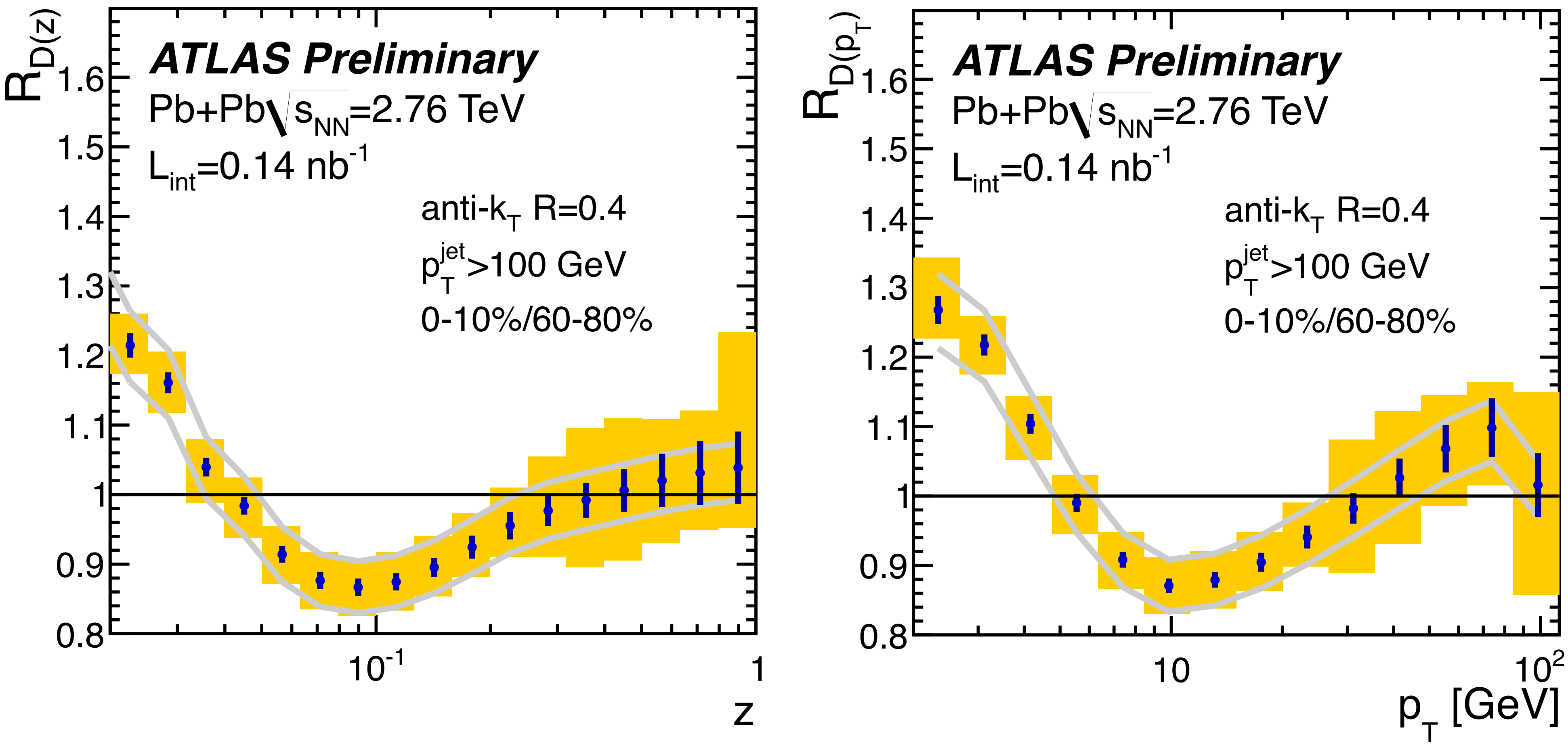
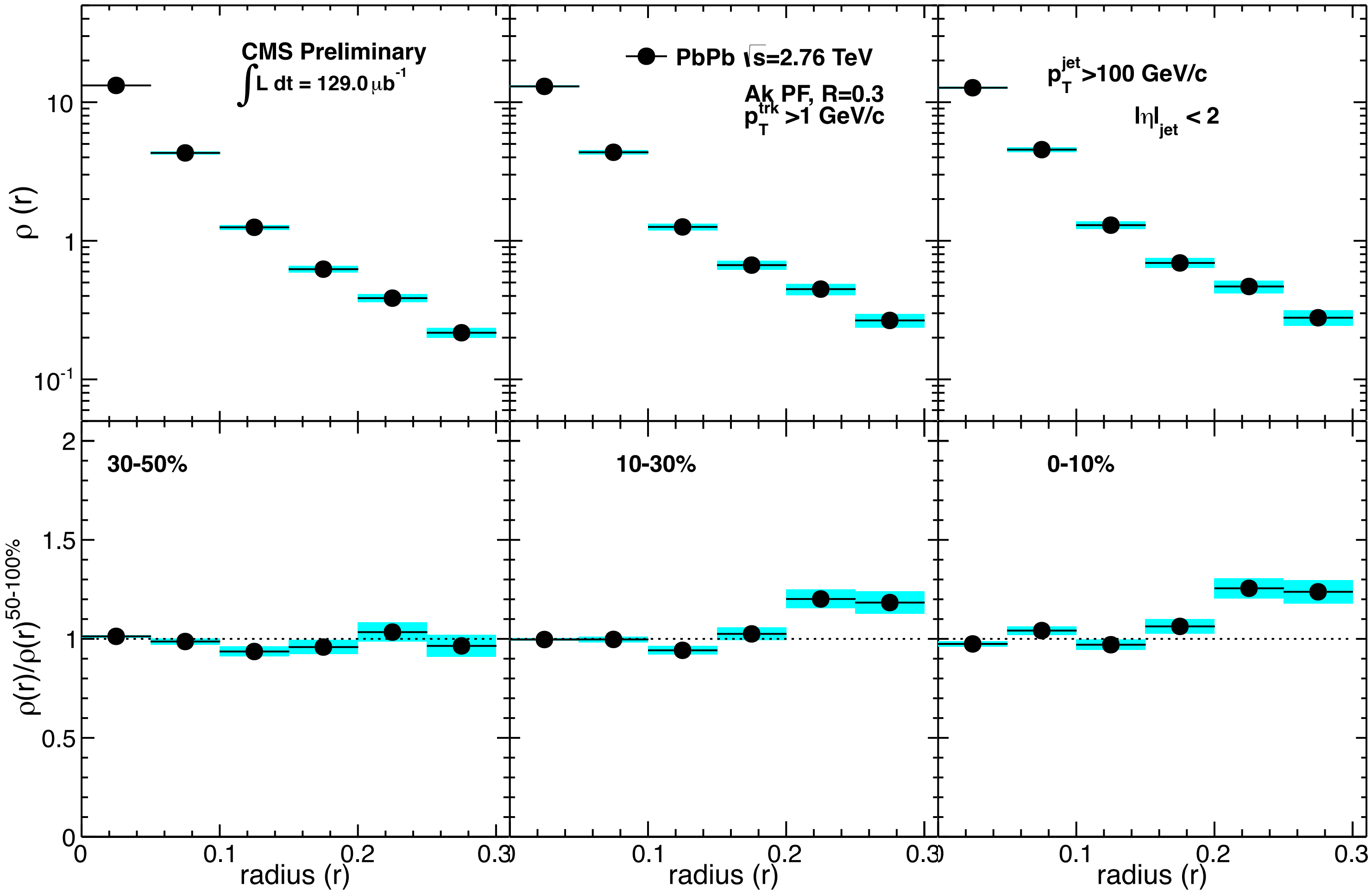
Jet Structure: Centrality Dependence

$$Ratio = D_{0-10\,\%} / D_{60-80\,\%}$$



- **Similar trends in *D(z)* and *D(p_T)* distributions**
- ***D(p_T)* does not have quenching effect in denominator**
  - **Slightly cleaner interpretation**

Jet Transverse Structure



$$\rho(r) = \frac{\mathrm{d}p_{\mathrm{T}}}{\mathrm{d}r}$$

- **Evidence for shape modification, more energy at larger radii**
  - **Qualitatively consistent with R_{CP} trends but what is quantitative expectation?**

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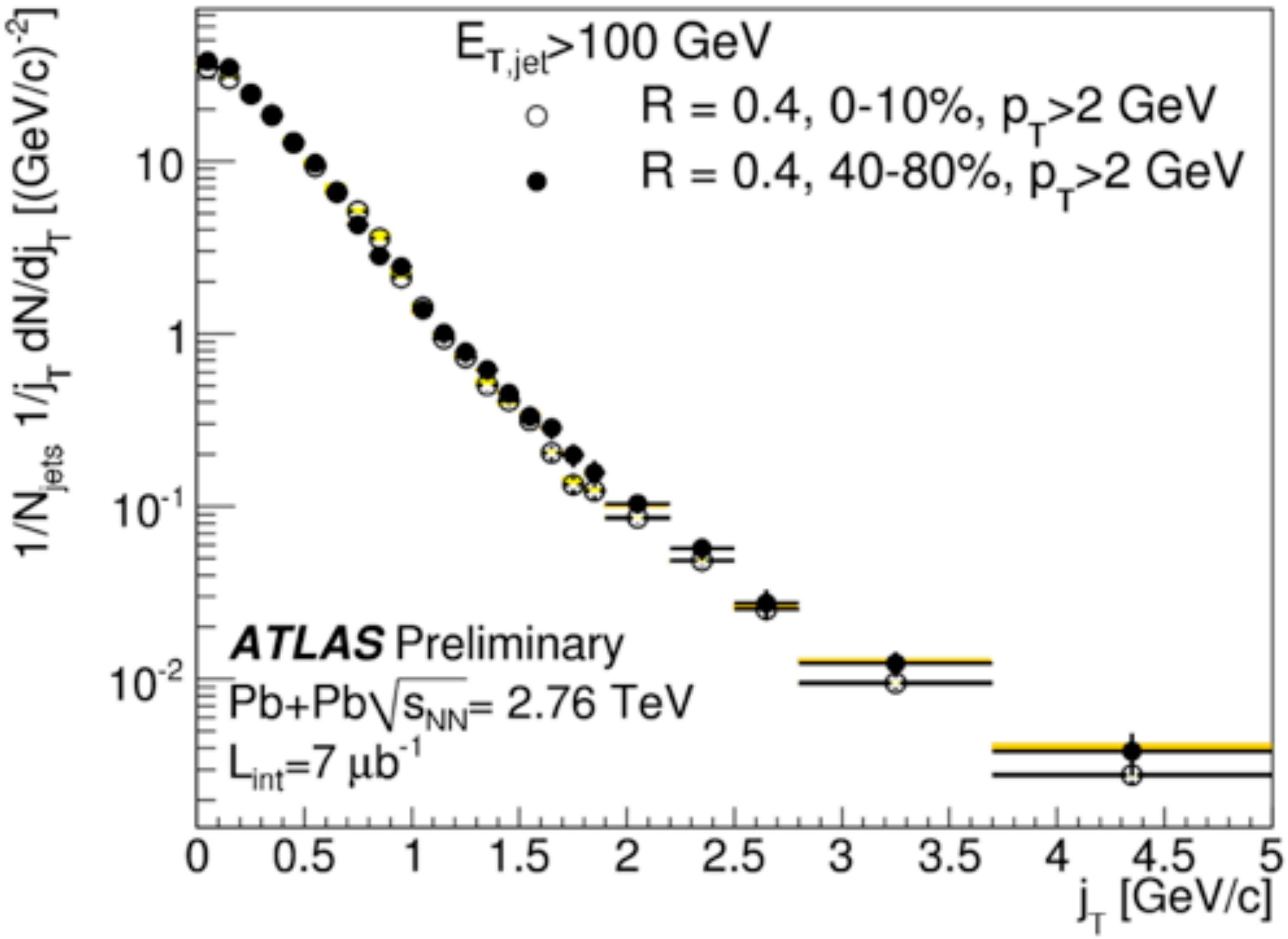
Jet Transverse Structure



- Consistent with small but significant centrality-dependent change in structure
- Measurement needs to be repeated using 2011 data

- Similar conclusion to jet shape
- Room for gradual broadening
- Needs precision measurement and quantitative prediction

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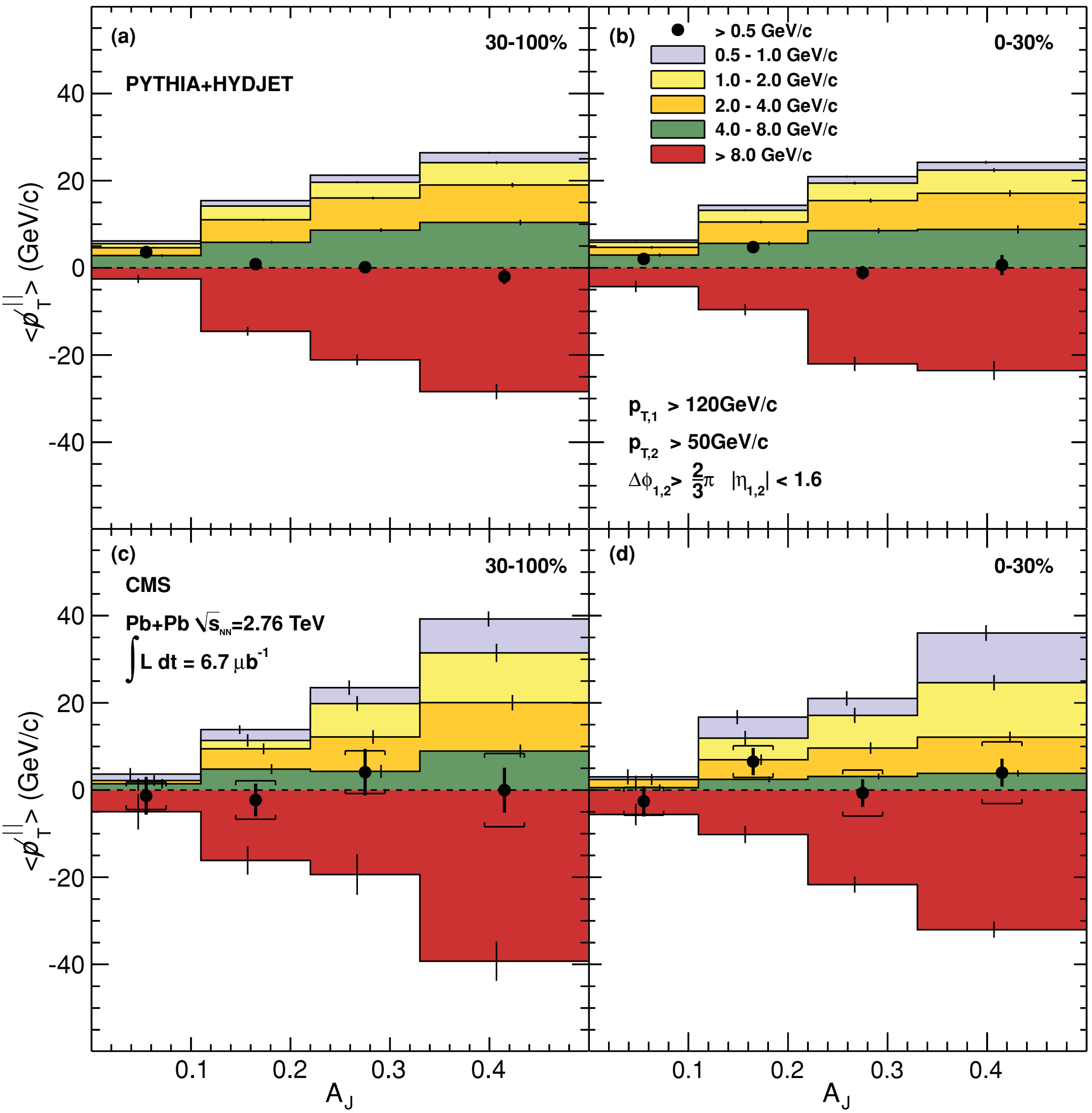
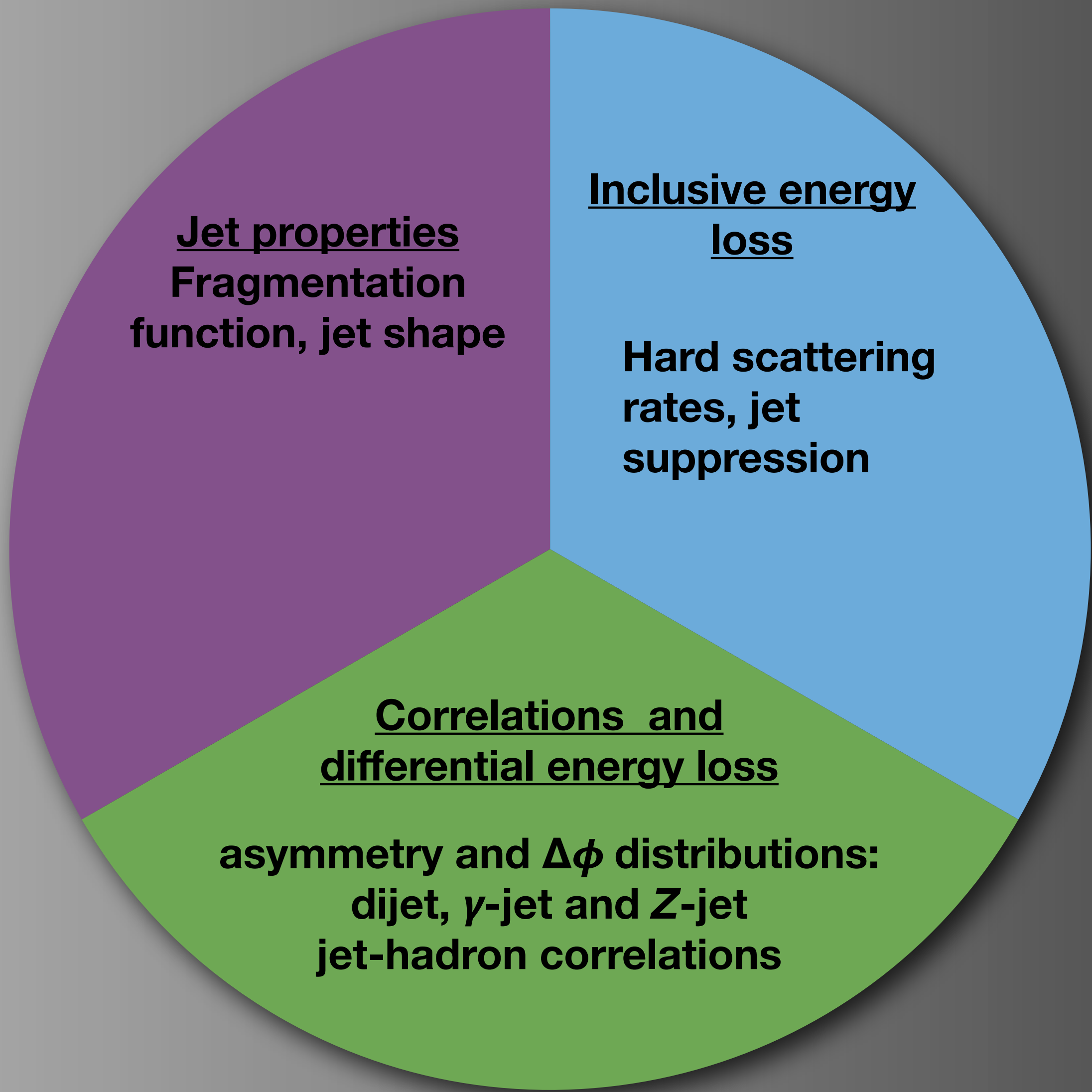
Jet Transverse Structure



- Not pure measure of transverse structure, but contains important informaiton
- Asymmetry analysis has shown that asymmetric dijet pairs recover momentum balance by including energy at large angles ($\Delta R > 0.8$)
  - ➡ Compared to unquenched this momentum balance is represented in softer particles

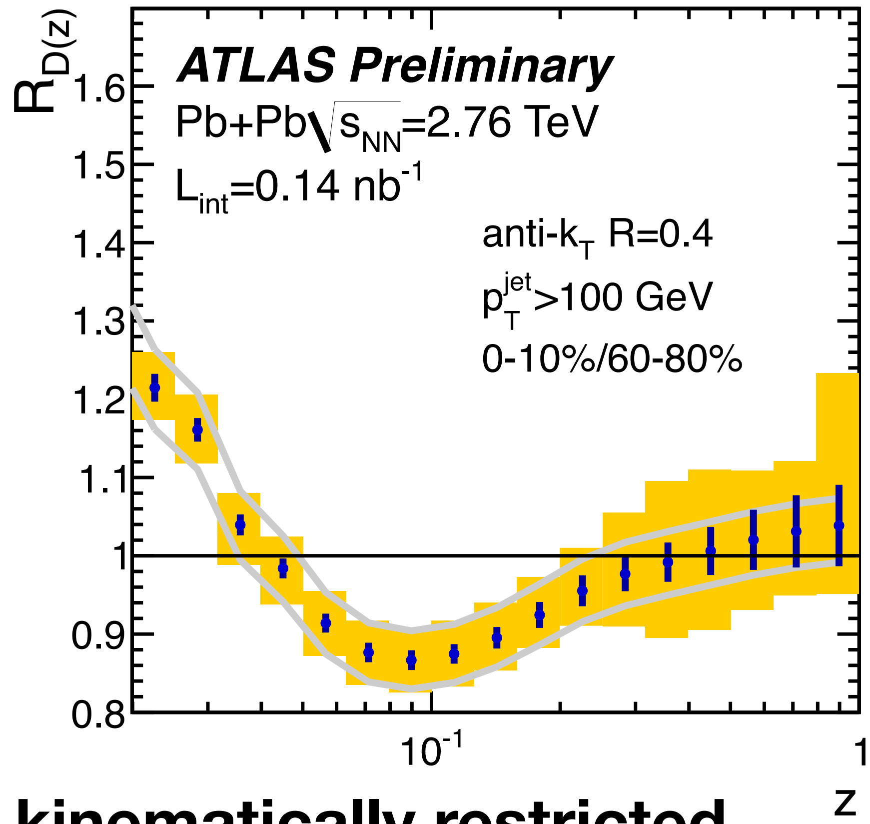
What are we left with after putting these together?



The "Average Jet"

- Tempting to interpret moderate *z* fragments losing energy and contributing to excess at low *z*
  - Would conclude all jets are quenched in the same way
- Not every jet has distribution of fragments like this

➡ In fact none do!



- Jets with fragments near *z*~1 are kinematically restricted from having additional fragments except at lowest *z*
- No guarantee that jets contributing to depletion are same jets contributing to excess

➡ Are jets with different parton showers/z/ξ distributions quenched differently/more likely to suffer less energy loss?

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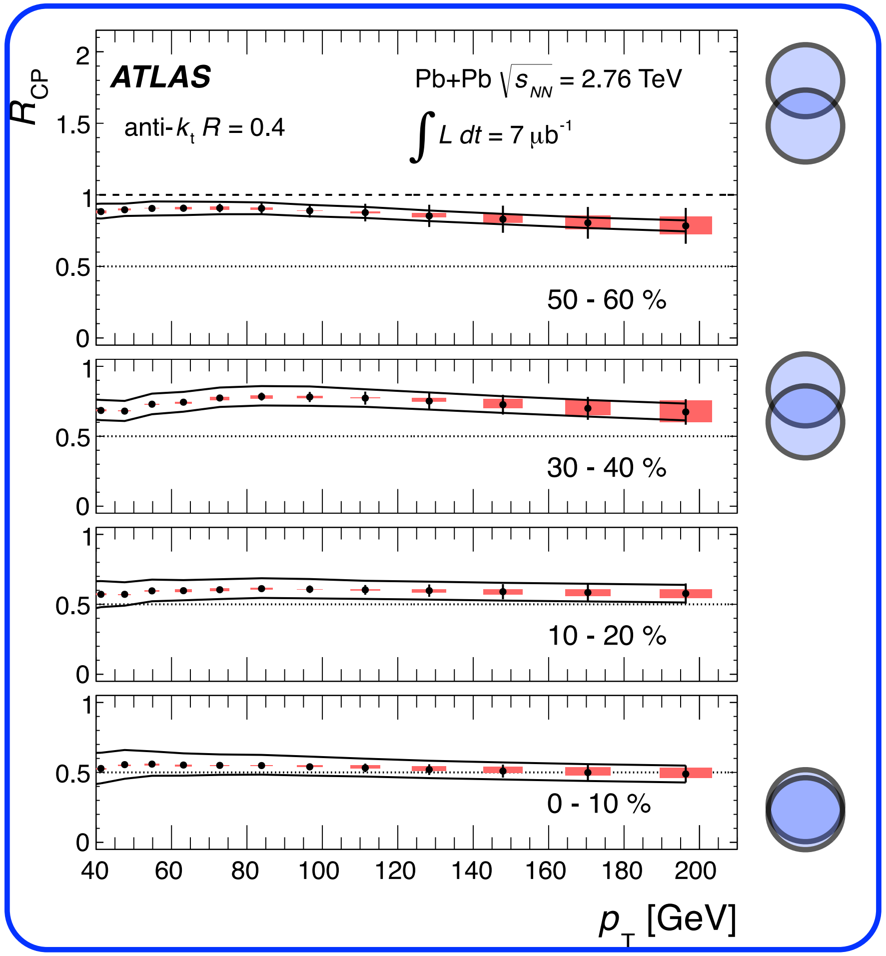
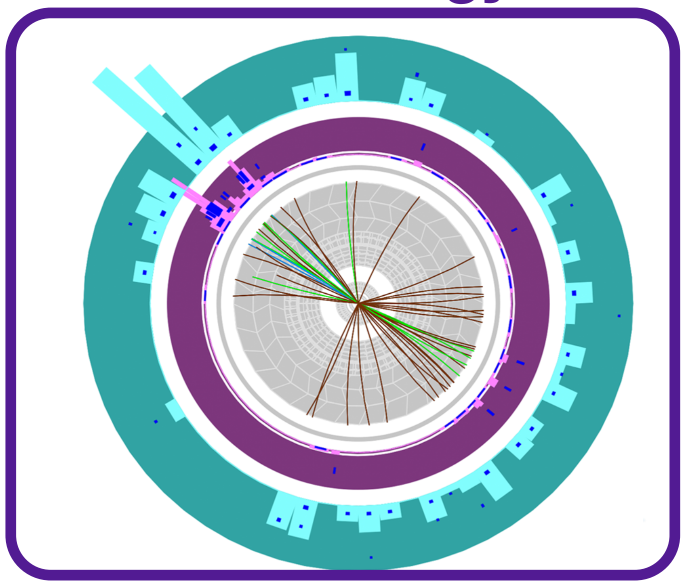
The "Average Jet"

- In HI we have event-by-event fluctuations in both the parton shower and the jet interactions with the medium

➡ <u>Key question</u>: Is quenching driven by average energy loss effects or by significant event-by-event variation not well represented by the average?



- Use suppression measurement with simple quenching models to give estimate of average energy loss
- Contrast with asymmetry observation : jets frequently lose more than 50% of their energy



R Dependence: Simple Energy Loss Model

- **Procedure adapted from PHENIX White Paper**
- **One way to get p_T independent R_{CP} is if energy loss is linearly proportional to p_T** $$p_{\mathrm{T}}^{\mathrm{f}} = (1 - S_{\mathrm{loss}})p_{\mathrm{T}}^{\mathrm{i}}$$
- **Assume power law for p_T dependence of spectrum**

$$\frac{dN}{dp_{\mathrm{T}}^{\mathrm{i}}} = \frac{A}{{p_{\mathrm{T}}^{\mathrm{i}}}^{n}}$$

- **Obtain n from fit**
- **Then S_{loss} can be inferred from measured R_{CP}**

$$S_{\mathrm{loss}} = 1 - {R_{\mathrm{CP}}}^{1/(n-1)} \qquad R_{\mathrm{CP}} = (1 - S_{\mathrm{loss}})^{n-1}$$

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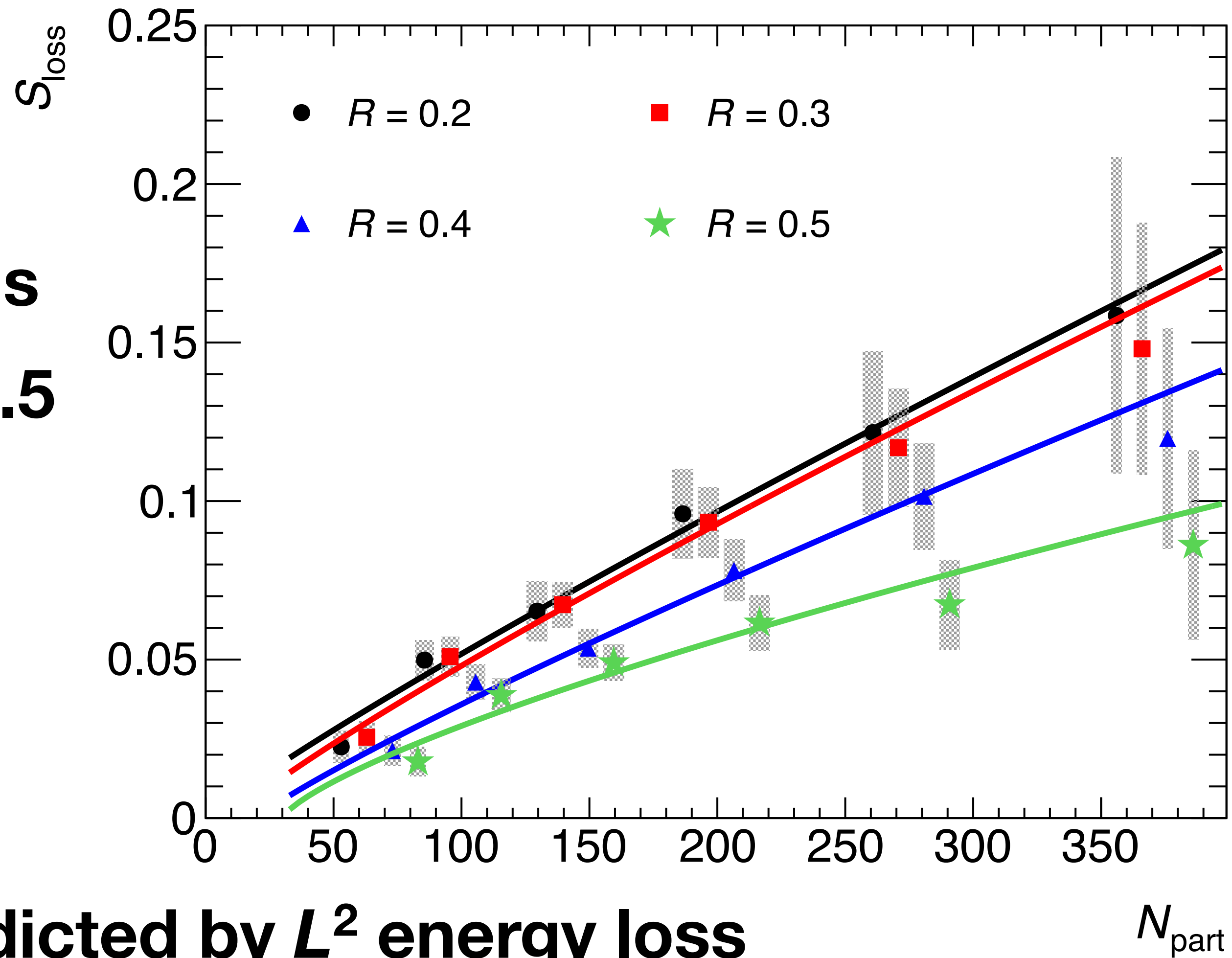
R Dependence: Simple Energy Loss Model

- **Indicates that jets on average lose 10-15% of their energy in the most central collisions**
  - **S_{loss} is lower for *R*=0.5 jets— they lose 5% less energy**



- **Fit with $S_{\text{loss}} \propto N_{\text{part}}^{k}$**
  - ***k* varies 0.75 — 0.9**
  - **Larger than 2/3 predicted by L^2 energy loss and seen in PHENIX result for single hadrons**
- ***Average energy loss not enough to account for observed asymmetry where jets regularly lose 50% of their energy***

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“Average” ≠ “Typical”

- Must be careful with interpretation of average especially in the case of jet properties
  - ➡ Ensemble averaged distribution may not be characteristic of individual event-by-event jet properties
  - ➡ Can be compared to calculation but may not be the best thing for building physical intuition
- Measurements of jet properties carry detailed information on quenching but characteristics of quenching may vary greatly from case to case
  - Utilize differential measurements to make stronger conclusions by restricting possible quenching scenarios
    - Already experimentally accessible (e.g. jet v_2)
  - ➡ Open question which observables are most sensitive to unknown aspects of quenching (e.g. radiative vs collisional)

Constraints on Models and Mechanisms

- Typical- vs fluctuation- driven quenching paradigm
    - How can measurements and calculations be more discriminating?
  - Large quenching effects still preserve dijet $\Delta\phi$ correlations
    - Rigorous approach considering full parton shower needed to describe LHC data
- *R* dependence of single jet suppression suggests *some* medium induced radiation recovered by going using larger jet definition
  - Supported by preliminary jet shape measurements
  - Conversely, asymmetry measurements show imbalance recovered in soft particles at large *R*
  - Need to be precise about energy being radiated away at "large angles"
    - Can such calculations also describe excess at low *z*/high ξ in fragmentation functions?
- Path length dependence needs serious investigation
  - How does *L* dependence survive integration over realistic geometry?

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